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Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0093

FIELD MEASUREMENTS OF MIXED EXPOSURE OF OPERATORS TO RADIOACTIVE AEROSOL, GAS AND QUARTZ IN CONFINEMENT OF MINING EQUIPMENT CABS DURING OPEN-PIT MINING OF HIGH-GRADE URANIUM ORES

by

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A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

RESEARCH REPORT

July 1982

FIELD MEASUREMENTS OF MIXED EXPOSURE OF OPERATORS TO RADIOACTIVE AEROSOL, GAS AND QUARTZ IN CONFINEMENT OF MINING EQUIPMENT CABS DURING OPEN-PIT MINING OF HIGH-GRADE URANIUM ORES

ABSTRACT

A series of field measurements of miners mixed exposure to radon and daughters, uranium ore dust and respirable quartz, was conducted in an open-pit mine in Northern Saskatchewan during 1980-81. Control of radon gas levels in the mining equipment cabs is required.

Dust may be reduced by minimizing the resuspension of dust from contaminated surfaces within the cabs.

RÉSUMÉ

Des mineurs exposés au radon et à ses produits de filiation, à la poussière de minerai d'uranium et au quartz respirable ont fait l'objet de relevés dans une mine du nord de la Saskatchewan, en 1980 et 1981. Les résultats indiquent qu'il faut surveiller le niveau du radon dans les cabines des véhicules miniers.

La poussière peut être réduite en minimisant la suspension nouvelle de la poussière en provenance des autres surfaces contaminées à l'intérieur de la cabine.

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INTRODUCTION

The tendency in mining methods of uranium being, or to be, employed in newly developed ore bodies in Northern Saskatchewan is predominantly by traditional open-pit operations with minor modifications. After stripping the overburden, a layer of waste as a shield of radiation from the underlying uranium ore layer of high concentration is left on top of the ore body. A variety of types of mining equipment, including backhoes, dumptrucks and bulldozers, is used for ore handling exclusively. Another set of equipment is used for waste material. (Cluff Lake B.I., 1978)

Operators of mining equipment are subject to exposure to radiation inside cabs of two major types: first; external irradiation to beta and gamma rays caused by exposure to uranium in the ore body or in the hopper of the dumptruck or by airborne radon gas and radon daughters, or internal irradiation induced by dermal intake: and secondly; the internal irradiation caused by the inhalation of radioactive aerosols and radon gas and daughters, or fine dust particles of uranium ore.

Factors affecting worker exposure to internal irradiation include: the content of uranium in the ore, the type of mining operation, the atmospheric conditions in the open pit, the protection factor of cab filters, the workers' attitudes toward radioactive substances, the cleanliness of equipment cabs and, above all, the properties of the aerosols and gases that emit alpha energy in the breathing zone of workers. Workers may also be exposed to dust clouds containing a mixture of radioactive aerosols and quartz (free silica). The overburden material at the mining site contains a substantial component of quartz which may become airborne in the process of mining operations. (Cluff Lake B.I., 1978)

Results of animal experiments indicate that respiratory exposure to a mixture of alpha emitting radioactive aerosols and quartz particles produced greater fibrotic changes in the lungs than exposure to radioactive aerosol or quartz alone. (Cross et al, 1978) Focus on the problems of exposure to radioactive sources in such high concentration might create a tendency to divert attention from the quartz content of dust in routine mining opera-

tions. The exposure to a mixture of these two hazardous materials in actual open-pit operations has been little studied. (Miller, 1977, Leach, et al, 1982)

Workers inside pressurized cabs of mining equipment are provided with filtered air through high efficiency particulate air filters (or HEPA filter) which collects DOP test aerosol of 0.3 micrometer diameter with an efficiency of up to 99.97%. However, there exists only a limited amount of scientific information on the field performance of such air filters intended for use in open-pit operations of uranium mines. (Yoshida, 1981)

Studies have been conducted on the characteristics of radioactive aerosols in underground mining including the particle size distribution of aerosols and the attachment of free atoms of radon daughters to these aerosols. However, the atmospheric conditions and the mechanisms of ventilation in open-pit operations have special characteristics which have been little studied in Canadian mines.

The purpose of this study then was: to investigate worker exposure to radioactive aerosols and gases containing alpha emitters, and to respirable quartz, in the open-pit mining of high-grade uranium ores; to attempt to identify the source of radioactive contamination of cab interiors; and, finally to present recommendations to control worker exposure to alpha emitters and quartz in high-grade ore handling.

A. Description of Mining Operations

1. Open-pit Operation

The "D" ore body at Cluff Lake is about 140 meters long, 25 meters wide and 8 meters thick according to a preliminary survey. The top or nose of the deposit is 6 - 7 meters beneath the surface, but dips from south to north at an angle of about 45 degrees. The uranium, in the form of pitch-blende, associated with organic matter, occurs in a pellitic formation characteristic of the bedrock underlying the Athabasca sandstone.

The "D" ore body is rich with an average predicted concentration of uranium of 7% by weight. Segments of ore body containing much greater concentration of uranium were mined during the course of this field work.

These ore bodies with extremely high concentration make the "D" deposit unique among known mineable uranium reserves in North America, and therefore special precautions to protect mine and mill personnel against excessive radiation are required. (Cluff Lake B.I., 1978)

The mining and stock pile site was fenced in and access to the area was controlled by security gates. Workers entered the work-site through a change house where they put on clean work clothing and personal dosimeters. The exposure subjects selected in this study all worked inside the enclosed area. (Cluff Lake, B.I., 1978)

The proposed grading of stock piles in the mining area is as follows:

a) Low grade: Less than 0.3% uranium and an average concentration of 0.11%

b) Medium grade: 0.3 to 20% uranium, with an average concentration of 4%

c) High grade: above 20% uranium, with an average concentration of 29.3%

Accordingly, the company set grading systems of ores to be transported to stock piles. Every truck from the ore site went through the grading scale which counted the activity with an overhead Geiger counter. These gradings are: grade A ore (375 - 7250 cps); grade B ore (7250 - 22500 cps); grade C ore (over 22500 cps); waste No.1 (zero count); waste No.2 (less 375 cps) respectively. The radioactivity of the ore body prior to excavation was

measured by a geologist to classify the operation and location of equipment specifically for ores or for waste materials. (Cluff Lake, B.I., 1978)

B. Equipment Used

1. Uranium Ore Mining - Equipment

A diesel powered conventional backhoe with a bucket capacity of 0.75 m^3 was used for loading broken ore from the mining surface into waiting dump-trucks. The backhoe excavated the ore body in a retreating manner, always being located on a flat and levelled surface. An eight ton bulldozer with ripper attachments was frequently used to loosen the side-wall of the ore body to assist the operation of the backhoe. It was also assigned to remove waste No. 1 or waste No. 2 materials partially covering the high-grade ores.

Two of the custom designed ore hauling trucks (Foremost Delta-3 dump-trucks made by Renn Manufacturing Co., Calgary) with heavy duty chassis of 15 tonne capacity and with a cab-controlled hydraulic system were used for the high-grade ore area. These trucks were each mounted with 6 balloon tires to cope with the rugged terrain of the mining sites. A rock drill (or jumbo drill) mounted on a backhoe boom was used for blast-hole drilling.

2. Methods of Worker Protection

All mobile equipment for use in loading and transporting ore had environmentally-controlled airtight operator cabs. The atmosphere in these pressurized cabs, in addition to being temperature controlled, was supplied with air through high efficiency particulate air filters (HEPA filters). The air was supplied to the cab through a systematic filtering system consisting of perforated inlets to remove foreign materials, an impactor plate to remove giant sand particles, a blower (made by Cincinnati Fan and Vent Co., model 6-BD, 20 cm fan diameter, centrifugal), a pre-filter (AAF 5700, 30 cm x 30 cm or equivalent type), and finally, a HEPA filter (AAF Astrocel, 30 cm x 30 cm or equivalent type). The air conditioning system inside the cab recirculated temperature-controlled air.

The control criteria was the gamma field above the protective blanket of waste. A sufficient thickness of waste material was required to maintain this level of gamma radiation. The hopper of the Foremost dumptruck was of the enclosed type and a mechanically-operated lid covered the ore container to prevent spillage or dusting during transport. Incorporated into the truck

design was a steel shield 6 centimeters thick, placed between the operator compartment (cab) and the ore hopper. The location of the hopper was spaced by an engine behind the cab to minimize radiation. A recording gamma counter was installed inside of the cab.

3. Waste Handling

A front-end loader with a bucket capacity of 2 m^3 was used exclusively for loading of waste materials (No.1 and No.2) and located away from the high-grade ore area. The loader was accompanied by two conventional dump-trucks of 15 ton payload (Wabco) to transport waste materials to the prescribed stock-pile site. Occasionally, the bulldozer, with a ripper attachment, was used to loosen some of the hard rocks. The average cycle-time of waste handling in normal operations was about 30 minutes.

4. Methods of Worker Protection

All of the equipment had pressurized cabs with filtered air supplied through HEPA filters during the period of investigation. There were no special arrangements to shield against gamma rays from the hoppers or buckets because the intrinsic shielding of the equipment was considered to be sufficient. These were used exclusively for waste materials.

C. Chronological Data of Field Work

1. Site Visit No.1: September 22-28, 1980

General atmospheric conditions inside the pit during this period remained cool and moist. The average air temperature was 10°c and the average relative humidity was 70%. During this period, both high-grade ores (up to 40%) and occasionally waste materials were handled. The posted radon daughter concentrations during this period ranged from 0.00 to 0.04 WL.

Samples were collected by means of an instantaneous reading working level meter, air bags and filters, a cascade impactor, a sequential air sampler, and an instantaneous read-out respirable mass monitor. (Table 1)

2. Site Visit No. 2: October 6-10, 1980

The type of operation during this period was mainly waste handling with occasional mining of low-grade uranium ores. The atmospheric conditions were very warm. (air temperatures at 25-30°c and relative humidities at 50-60%) The values of radon daughter concentration posted at the entrance of the pit ranged from 0.00 to 0.02 WL. Samples were collected by the filter

method outdoors and inside the cabs, by air bags for outdoor background sampling, by filter and cascade impactor for quartz mass concentration and particle size distribution and by an instantaneous read-out respirable mass monitor for grab sampling outdoors and inside the cabs. Wipe samples were collected at various interior surfaces of cab. (Table 1)

3. Site Visit No.3: July 15-19, 1981

The visit was intended to investigate the particle size spectrum of aerosols in the working environment in the open-pit in dry and warm atmospheric conditions (air temperatures 20-25°c, relative humidities 30-50%). Operations included handling of high-grade uranium ore, waste materials and drilling of blast holes. During this period, the values of working levels posted were 0.00 to 0.04 WL. All equipment was operating with the air conditioning at full capacity. Samples were collected by means of a cascade impactor and by filters and air bags. The instantaneous read-out respirable mass monitor was also used. Sampling was done inside the cabs to investigate airborne particulates. (Table 1)

4. Site Visit No.4: August 5-10, 1981

The last visit was intended to add further detailed information on the particle size spectrum and the morphology of quartz containing dust, to characterize open-pit aerosol and to investigate the air flow pattern of cabs and the resuspension of aerosol inside the cabs. The weather stayed very hot (air temperatures 25-30° c and relative humidities at 30-60%). Operations included waste handling and low-grade ore handling; however high-grade (C) ores were handled on August 8th and 9th. The posted value was 0.361 WL in the morning before the high-grade ore operation commenced. Simultaneously with air flow tests, a series of wipe tests was made in all the mining machines. Additional samples were collected inside the cabs by cascade impactors. (Table 1)

D. Mechanisms of Worker Exposure

1. Source of Worker Exposure - Radioactive Aerosols and Gases

In general, radon concentrations are lower in open-pit mining operations than in underground mines, since the radon gas released from the ore body can be dispersed quickly in the atmosphere. In preliminary investigations in the "D" ore body, the concentration of radon and its daughters at 1 meter above the highest grade ore was 20 pCi/L and the daughter concentration in-

dicated 0.01 WL. (Cluff Lake B.I., 1978)

2. Airborne Quartz and Uranium Dust

Potentially hazardous agents of major concern in this study in open-pit mining include dusts of sandstone containing free silica (or quartz) arising from drilling, blasting and removal of waste rock from the area surrounding the ore, radioactive dusts from the uranium ore.

The ambient air quality standards of Saskatchewan provide for an annual geometric mean concentration of suspended particulate matter of 70 $\mu g/m^3$. Previous investigation at the Cluff Lake site indicated that the background level of airborne dust ranged from 1 to 25 $\mu g/m^3$. The dust concentration during mining operations could reach 10 times the general background at 250 $\mu g/m^3$. The absolute concentration of quartz in such dust could be 12.5 $\mu g/m^3$ if the respirable quartz content of such airborne dust were 5%. (Cluff Lake B.I., 1978)

3. Routes of Worker Exposure - Filtered Air

Even though high efficiency particulate air (HEPA) filters are used in the pressurized cabs of mining equipment, a worker inside the cab may be exposed to radioactive gas. HEPA filters possess a superiority over conventional air filters in the following aspects: ultra-high efficiency of collection, low pressure drop, and high ratio of filter area to face area. HEPA filters operate on the impact diffusion principle and utilize a high ratio of media area to face area. The velocity through the medium is limited to a maximum of 0.03 m/sec to provide a high dust holding capacity and long filter life.

The HEPA filter provides respiratory protection of workers against radioactive aerosols and dusts. However it is no defense against radon gas. The reduction of potential alpha energy through a HEPA filter can be calculated by the following equations:

The potential alpha energy (E) measured before the HEPA filter in the outdoor environment in working level (WL) is (Key Lake B.I., 1980),

$$E = F \cdot C$$

Where (F) is the equilibrium factor and (C) is the concentration of radon gas ($pCi \cdot L^{-1}$)

As the time (t) elapses, daughters are formed and the equilibrium factor increases as a function (Ø) of time, then

$$F = Ø\ (t)$$

When a gas mixture enters a filter, the potential alpha energy (E_o) is,

$$E_o = F_o \cdot C_o$$

Where (F_o) is the initial equilibrium factor and (C_o) is the initial concentration.

The potential alpha energy after filter (E_1) is,

$$E_1 = E_o \cdot f^{-1} = (F_o \cdot C_o)\ f^{-1} = F_1 \cdot C_o$$

Where (f) is the ratio of particulate entering to particulate out

(F_1) is equilibrium factor after filter

$$f = F_o \cdot F_1^{-1}$$

The apparent age of radon (t_1) is, then

$$t_1 = (F_o \cdot f^{-1}) \cdot Ø$$

For HEPA filter, (f) $\rightarrow$ infinite and $t_1 \rightarrow o$

The potential alpha energy in (WL) after the filter (E_2) is,

$$E_2 = C_o \cdot Ø \cdot (t_1 + t_r)$$

Where t_r is residence time of radon between the source of generation and the point of measurement.

The reduction (R) of potential alpha energy is, then

$$R = E_2 \cdot E_o^{-1} = C_o \cdot Ø \cdot (t_r + t_1) \cdot (F_o \cdot C_o)^{-1}$$

In determining of (R), measurement of the potential alpha energy (E_o) of gas mixture before entry and after the filter (E_2) are required. By assuming that highest alpha energy of outdoor gas in the vicinity of equipment cab is (E_o = 0.34 WL) while mining high-grade ore, and that the collection efficiency of filter system used with the cab is maintained at 99.97%, potential alpha energy after filter inside the cab is,

$$E_2 = (1-R) \cdot E_o = 0.000102 \text{ WL}$$

The value of alpha energy of airborne aerosols thus determined is considered to be atmospheric background (Fry, 1975)

4. Resuspension of Aerosols

Dust particles that penetrate the filter are either deposited on surfaces inside a cab through mechanisms such as diffusion, inertia, gravity, interception, and electrostatic attraction are circulated in the ventilating air-stream and later deposited or leaked out of the cab.

Mass or radioactive concentration of aerosol in the breathing zone of a worker inside the cab (C_{BZ}) is attributed to the initial concentration of aerosol in the cab (C_1), the concentration through the HEPA filter (C_c) and the concentration in the leaking air and the exhaust system of cab ventilation (C_e). For equipment in operation, equilibrium between the various concentrations will be attained only after a steady state of the air flow and the air circulation in the cab is established. Then for aerosols, the breathing zone concentration is:

$$C_{BZ} = C_1 + C_c + C_r + C_e$$

where C_r is the concentration of aerosol through resuspension; for gases

$$C_{BZ} = C_1 + C_c + C_e$$

Most of the quantities in the above 2 equations are easily measureable in field conditions except C_r. The turbulent bursts which are generated within the core region of cab confinement cause resuspension of dust from surfaces. Particles are resuspended by sliding, rocking, rolling, bouncing, by sudden ejection, or by some combination of these movements. Nevertheless, the adhesion force between the particles and the surface ought to be overcome by the ejection forces before ejection takes place. The motion of particle resuspension from a surface may be expressed in a generalized form as:

$$C_r = f(Uz \cdot R \cdot D \cdot H)$$

where Uz is the surface roughness parameter, D is the aerodynamic diameter of the particle, and H is the frequency of the surface air burst, respectively.

A review of in-depth studies has been completed for cabs used in farm tractor on the dust resuspension theory but such treatment is outside the scope of this study. From the results of previous studies, it is expected that a considerable fraction of airborne dust inside the cab confinement in such dusty operations could originate from contaminated surfaces by means of resuspension. This aspect of the study, particularly in mining equipment cabs, is relatively new in the field of aerosol technology and requires further investigation. (Atiemo et al, 1978, Atiemo et al, 1981)

5. Surface Contamination

Radioactive dust once introduced into a cab confinement may also settle on surfaces. Airborne radioactive gas also may contaminate various surfaces inside the cab. These radioactive agents may be transferred by skin contact to the human body. For high-grade ore of 7% concentration, 0.3 mg/cm^2 of dust deposit may present the maximum permissible surface contamination. (Cluff Lake B.I., 1978)

Two types of mining equipment are used: one exclusively for handling high-grade ore and another for waste handling only. This practice does reduce cross-contamination of mining equipment to a great extent; however, the degree of surface contamination should be investigated by wipe tests which have been commonly used in nuclear installations.

E. Sampling and Analytical Methods

1. Strategies Established - Personal and General Air Sampling

The existing health regulation require that worker's exposure be measured by any combination of long-term or short-term samples that represents the worker's actual exposure. Air samples should be taken in the worker's breathing zone (air that would most nearly represent that inhaled by the worker). In personal or breathing zone sampling, the sampling device is directly attached to the worker and worn continuously during all work and rest operations. The general air sampling is done with a stationary sampler in the work area. (NIOSH. 1977)

If samples taken by the general air method are to be used to determine worker exposure, then it is necessary to demonstrate that they accurately measure worker exposures. Generally this involves a comprehensive job time-motion study for each worker repeated at least every 3 months. Then a comparison must be made with personal or breathing zone samples to show equivalency. There are 4 types of sampling for exposure determination: full period single sample, full period consecutive samples, partial period consecutive samples, and grab samples. There is no such thing as one best strategy for all situations; however, some strategies are clearly better than others. In this study, the method of partial period consecutive samples were collected. (ACGIH, 1981)

2. Background Sampling

The air quality of a mining site or that in the vicinity of mining activity is investigated prior to the commencement of air sampling in the work environment to obtain the levels of general background of suspended particulate matters and radioactive aerosols and gases. For suspended particulate matter (airborne dust), full period single samplings are required. The continuous sampling period used for such purpose in air pollution field work is 4 days (24 hours a day).

However, the general background of radioactivity could only be monitored by grab sampling or partial period consecutive samplings due to the time required for sample preparation and counting.

3. High-grade Ore Handling

Owing to the time period required for radioactive decay and counting of samples after collection, and to the fact that there was only one field counter available for handling both air bag and filter samples, the sampling method was short-period sampling (15 minutes) which is intended for short-term average concentration. (NIOSH, 1974)

4. Waste Handling

Samples to be collected in waste handling are mainly for gravimetric and size analyses; therefore only short-period (30 minutes) or grab samples were required, except for particle size analysis which requires longer periods of sampling (1-3 hours) to obtain sufficient mass of dust particles on the impaction stages for smaller sizes for gravimetric analysis due to the sensitivity of 10 μg with an automatic electronic balance.

5. Counting Sequence

A compromise was required in setting sampling sequence and timing of radioactivity counting, because once the sampling sequence was established for one set of mining operations, the number of samples to be collected was limited by the time required for radioactive decay and counting which could overlap the schedule of subsequent field work. Counting was done exclusively in a clean room remote from the mill site.

F. Sampling and Analytical Methods Used

1. Suspended Particulate Matter

Prior to the commencement of pit sampling, a stationary sampler was located and operated during the entire period of visits in the vicinity of

the central office area. The sampler was intended to sample suspended particulate matter (dust) in 5 elevations up to 2.5 m above the ground. Membrane filters (Millipore, type AA, 25 mm, 0.8 µm pore size) were aspirated at 3.0 L/min. during the entire period of outdoor work and the mass concentration of airborne dust was determined gravimetrically.

Dust concentration was also measured by using an instantaneous read-out respirable mass monitor (TSI model 3500) as spot sampling inside the cabs and outdoors. The inlet of the mass monitor was kept both in the breathing zone of workers and in the general outdoor area.

2. Radioactive Gases

Tedlar airbags (2 litre capacity) with a known absorption rate of radon gas were used for gas sampling and aspirated with a portable pump (Spectrex model PAS-3000) at the rate of 100 mL/min. for 10 to 20 minutes. A membrane filter (Millipore AA) was attached to the suction inlet of the pump to prevent the entrance of particulate matter into the airbags. After a period of radioactive decay not exceeding 24 hours, the contents of the airbags were transferred to evacuated Lucas cells (Pylon model 110, 160 cc) for counting. The counting efficiency of cells was 85%.

A portable field counter (Pylon model RM-1003) was used for all the counting (gross alpha) of Lucas Cells. Usually a single count of 20 minutes was repeated 4 to 5 times. Airbags aspirated by a sequential sampler (Research Appliance Co., model PV-2, 12 ports 7 L/min.) were also treated in the same way to determine the concentration of radon gas.

3. Short-lived Radionuclides (Radon Daughters)

The method used was based on the Kusnetz method for short-term discrete sampling. The same membrane filters (Millipore AA) were located in the breathing zone and aspirated at 3.0 L/min. for 15 minutes; then after a period of radioactive decay of 90 minutes or longer, the filters were mounted on saddles specially supplied for the field counter (Pylon RM-1003). The counting efficiency of the zinc-sulfide detector was 35%. (Budnitz, 1974)

Also inside the cabs and in the vicinity of the mining equipment, an instantaneous read-out working level monitor (Pylon WL 1000B alpha spectrometer) was used to determine the concentration of radon daughters. The monitor was used during the first site visit only by a technologist from CANMET, Department of Energy, Mines and Resources, Ottawa.

A cascade impactor (Sierra model 266, 6 stages) was aspirated at 8.5 L/min on various occasions in the breathing zone and the outdoor environment. The mass deposited on each stage (Teflon sheet substrate) was analyzed gravimetrically for mass median aerodynamic diameter (MMAD) and counted later by alpha activity for the activity median aerodynamic diameter (AMAD) of aerosols attached to short-lived radionuclides.

4. Long-lived Radionuclide (Uranium Ore)

Dust samples collected inside and in the vicinity of mining equipment on membrane filters were gravimetrically analyzed for the total mass concentration. Then the mass on the membrane filter was analyzed at SRC's Slowpoke neutron activation facility (sensitivity is 0.2 μg per analytical sample) for the presence of uranium ore (or long-lived radionuclides). Membrane filters with uranium ore-containing dust were transferred from each stage of cascade impactor and were analyzed with the neutron activation method to determine the values of activity median aerodynamic diameter (AMAD) for uranium ore dust.

5. Free Silica (Quartz)

Sampling activities for free silica were mainly in the waste handling areas; however several samples using the cascade impactor were taken inside the cabs for this purpose. The same membrane filters (Millipore AA) were used at higher flow-rates to obtain larger masses of dust in shorter sampling periods, which represent a typical operation. The samples of dust collected on membrane filters were ashed at a lower temperature and the residues were redistributed onto silver membrane filters (Flotronic, FM-47 mm, 0.8 μm pore). Each sample was then scanned by x-ray diffractometer to determine the concentration of free silica. The mass of free silica in the sample was determined by an area of XRD graph and by comparing to the peaks of standard reference material. The limit of detection of free silica for the XRD instrument used was less than 5% of the total sample. (NIOSH, 1975)

6. Surface Contamination (Wipe Test)

The principle of a wipe test was taken from OSHA standard method of skin absorption monitoring - wipe sampling policies and procedures. Nitrocellulose filter papers (Whatman No. 3, 12.7 mm) were wetted with deionized distilled water and 100 cm^2 of selected surfaces of the cab were wiped once. The samples collected were counted 2-3 weeks after sampling with the field

counter for the presence of uranium ore dust or long-lived radionuclides. The alpha activity per unit cm^2 of surface was thus determined. (AERE, 1963)

The air flow pattern and velocity profile inside the cabs were investigated by using a hot-wire anemometer at various surfaces of different orientation and physical properties. The same anemometer was connected to a chart recorder to investigate the air burst frequency at various surfaces at various blower settings of the air conditioning system.

7. Particle Morphology

Dust samples collected both in high-grade and waste handling areas were prepared for analysis with a scanning electron microscope (SEM, Cambridge model Mark II-B with energy dispersing x-ray analysis capability). The samples were gold-coated and scanning electron micrographs of particles or images of pin-pointed particles were obtained to identify uranium and quartz. (NIOSH, 1975)

G. Environmental and Occupational Standards

1. Suspended Particulate Matter

Suspended particulate matter is a general term applicable to a wide variety of solid or liquid particles of size and configuration such that they tend to remain suspended in the air and could be drawn into the respiratory passages. By general agreement, the use of term set by Environment Canada is restricted to particles under 100 μm in diameter. Therefore, the definition excluded substances with known specific toxic effect and referred only to those which are chemically inert.

The maximum acceptable level (MAL) is intended to provide adequate protection against effects on soil, water, vegetation, materials, animals, visibility, personal comfort and well being and was set at 120 $\mu g/m^3$ as an annual geometric mean and used on a day to day basis.

2. Radon and Daughters

The Saskatchewan regulation is based on the report by the International Commission of Radiation Protection (ICRP) which recommended a formula for the maximum permissible concentration (MPC) (airborne) of radon and indirectly its daughters which take the degree of attachment into account. Thus the MPC in air of radon and its daughters, for a 40 hour week is calculated as 4 WL months. (Sask. Department of Labour, 1981)

3. Uranium Ore Dust

Uranium-ore dust concentrations in the air of work areas recommended by Labour Saskatchewan for soluble and insoluble natural uranium is 0.2 mg/m^3 as an 8-hour average contamination limit. The concentration of 0.07 pCi/L activity is equivalent to 0.2 mg U-natural/m^3. (Sask. Labour, 1981) The limit of the ore dust in the air is difficult to establish since it must take into account the state of equilibrium of each element of the uranium chain.

4. Surface Contamination

There are no internationally accepted values for the limit of skin and surface contamination by alpha emitters. The limit recommended by IAEA and used by the University of Saskatchewan for the skin contamination (removable) by alpha emitting radioisotope is 10 pCi/cm^2 and 1000 pCi/cm^2 for surfaces. (IAEA, 1976) (Table 2)

5. Respirable Quartz

The threshold limit value (TLV) of 0.1 mg/m^3 quartz concentration for an 8-hour time weighted average is proposed by Labour Saskatchewan. For dust particles containing less than 1% mass of quartz, TLV's for nuisance particulate at 10 mg/m^3 of total dust or 5 mg/m^3 of respirable dust are applicable. However, the content of quartz in over-burden or waste materials is already known to exceed the 1% level. TLV for total dust is, TLV = (30 mg/m^3) / (% quartz + 3) and TLV for respirable dust is TLV = (5 mg/m^3) / (% respirable quartz + 2). TLV's will be determined according to the content of quartz and the data obtained in the field samplings and will be evaluated. (ACGIH, 1981)

6. Combined Exposure Limit

In case two or more substances are present in the work environment, their combined effect, rather than individual effects, should be given primary consideration. The ACGIH maintains that in the absence of information to the contrary, the effects of the different hazards should be considered as additive. That is, if the sum of the following fractions, exceeds unity, then the threshold limit of the mixture is exceeded.

$(C_1/T_1) + (C_2/T_2) + \ldots\ldots\ldots (C_n/T_n) \geq 1.0$ where C_1, C_2 ..... C_n are the observed concentrations of the individual contaminants, T_1, T_2 ... T_n are the corresponding threshold limit values for the individual contaminants.

In this context, the TLV refer to the airborne concentrations of substances and represents conditions under which nearly all workers can be repeatedly exposed daily without adverse health effects. Thus, the combined TLV concept by the ACGIH is applicable to chemical agents only.

Therefore, for the respirable aerosol with a mixture of uranium ore and quartz, the TLV may be determined as,

$$TLV = \frac{1}{\frac{(\text{Natural Uranium conc.})}{0.2} + \frac{(\text{Resp. Quartz conc.})}{\left(\frac{10}{100 \div 2}\right)}}$$

H. Results and Discussion

1. Background Concentration - Total Dust

The mean concentration for the total mass of dust in the vicinity of "City Hall" (mine office area) during all site visits was on the order of 0.01 mg/m^3, except on one hot, dry and windy day when the general background was up to 0.34 mg/m^3. Otherwise, the mean value of concentration for all the sampling days was 0.02 mg/m^3 which was lower than the annual geometric mean of suspended particulate matter (Maximum acceptable limit) set by the Environment Canada by assuming a log-normal distribution of such occurrance.

However, the concentration of airborne dust inside the pit varied according to the type of major operation of the day. The highest concentration occurred when there was drilling (0.04 - 0.5 mg/m^3) and waste handling (0.1 - 0.4 mg/m^3), otherwise the dust concentration in ore handling was relatively low (0.01 - 0.05 mg/m^3) since the road surface always remained wet when being used according to the company's standard safety practice.

2. Radioactive Aerosols and Gases

There was no detectable level of radioactivity in the dust samples collected in the vicinity of "City Hall" (mine office area) for the entire period of the site visit. However the radon daughter concentration inside the pit at the center remained at 0.0001 to 0.01 WL. Day-to-day variations of radon concentration at the bottom of the pit in the vicinity of the ore body were recorded by the company. The values showed peak values early in the morning before miners proceeded into the pit and rapidly dissipated after mid-morning when the winds rose.

3. Physical Condition of Ambient Air

In summary, the weather during the first visit was cool and wet, then hot and dry in early October of 1980 for the second visit, followed by hot, dry and windy periods in mid July of 1981 for the third visit, and finally again hot and dry periods in early August for the final visit. The mean values obtained were only for the mining period (7:00 a.m. to 7:00 p.m.) inside the fence, in the vicinity of the pit. Measurements of temperature, relative humidity and wind speed were made in the vicinity of the equipment. (Table 1)

I. Work Environment and Breathing Zone

1. Total Dust

The concentration of total airborne dust inside cabs of all the equipment remained lower than 1 mg/m^3 and this level was far less than the threshold limit value (TLV) of nuisance particulates set by the ACGIH (10 mg/m^3 as TWA).

The dust concentration inside the cabs divided by the concentration outdoors ranged between 0.10 - 0.30 levels except on July 17, 1981 which was a hot and very windy day resulting in a higher value. (Table 4)

2. Radioactivity of Aerosols and Gases - Outdoor

The concentration of radon gas inside the pit, in the vicinity of the backhoe which was excavating high-grade ores (grade C), ranged from 25 to 300 pCi/L in the morning of September 23, 1980. The weather was wet and cool in the morning and the posted value at the pit was 0.03 WL. (Table 5)

During a 3-day period in the first site visit (September 22-24, 1980), alpha spectrometric measurements of radioactivity in the vicinity of high-grade ore were taken with the help of a CANMET technologist. There was no appreciable presence of thoron inside the "D" pit. In spectrometric counting of radon daughters, the instrument encountered some problems due to damp and cold conditions of the day. The concentration of radon daughters remained at 0.0001 WL in the vicinity of the high-grade ore body and inside the Foremost dumptrucks. (Table 6)

3. Concentration of Radioactive Aerosols and Gases - Backhoe

The concentration of alpha activity of radioactive aerosols during the period of the site visit ranged from 0.001 to 0.1 WL for high-grade ore mining.

Radon gas concentration was up to 33 pCi/L. The highest activity inside the backhoe cab was 0.094 WL on August 8, 1981. Posted activity in the morning at 7:30 a.m. was 0.12 WL. The activity inside the cab was not always lower than the outdoor environment, but fluctuated widely. (Table 7A) The rate of air change of equipment cab was set at 4 air changes per minute. The discharge rate of the fan through the HEPA filter was accordingly set to maintain the proposed rate of air change. (Kreb. 1971) The pressure drop over the HEPA filter was kept at 1.25 to 2.5 cm water.

4. Dumptruck (Foremost)

The concentration of alpha activity inside the cab of the 2 dumptrucks ranged from 0.001 to 0.1 WL while being assigned in mining high-grade ores. The highest level of alpha activity was 0.089 WL on July 18, 1981. Two sets of samples were collected on July 18, 1981, including inside and outdoor. The outdoor air contained a higher level of radon (45.6 pCi/L), while the inside air contained only 5.66 pCi/L. (Table 7B)

5. Bulldozer

Bulldozers with ripper attachments were used both for waste and ore mining operations, however samples were collected during the ore mining operations. The alpha activity ranged from the order of 0.01 to 0.1 WL. The concentration of activity reached 0.09 WL on July 19, 1981, was caused by the fact that the bulldozer was working in the vicinity of high-grade ore body. Posted working level in the morning at 7:30 a.m. was 0.277 WL. (Table 7C)

6. Equipment used in Waste Handling

The concentration of alpha activity inside the drill, was 0.004 WL, on August 11, 1981, while the level in the front-end loader was at 0.01 WL on July 16, 1980. Wabco dumptrucks that were never used for high-grade ore handling had levels of 0.008 to 0.015 WL. The posted working level of the day was 0.04 WL. (Table 7D)

J. Particle Size Distribution

1. Total Dust

The range of mass median aerodynamic diameter (MMAD) of the airborne dust in the open-pit environment was from 0.6 to 3.3 μm. The dust particles had a geometric standard deviation (σg), which is a parameter to indicate

the uniformity of size distribution, ranged from 3.8 to 8.5. The respirable mass fraction was 62 to 83% of the total airborne dust. The characteristic of the dust is typical of mechanical dispersion though accompanied by minor contribution of condensation by the exhaust emission of diesel engines of mining equipment. (Table 8, Figures 1A, 1B & 1C)

The MMAD of dust particles trapped inside cabs of mining equipment remained at the same order of magnitude compared to the outdoor dust; they are: 2.3 μm for the bulldozer and 1.8 μm for the backhoe, respectively. The values of σ_g determined inside the equipment cabs also agreed closely with the outdoor values. The respirable mass fraction of dust inside the cabs was at the 70% level. (Table 8, Figures 2A & 2B)

While some transmission of small particles of dust may have occurred through the HEPA filter into the cab, the close agreement of particle characteristics between outdoor and inside supported the concept that dust resuspension from surfaces within the cab was a major contributor, however, leakage and resuspension of dust brought in as contamination on boots may also be considered as the secondary contributor.

2. Radon Daughters

The value of activity median aerodynamic diameter (AMAD) of radon daughters in the vicinity of mining equipment of an open-pit environment was 0.03 μm when the high-grade ore was being mined on a cool, wet day. Atmospheric conditions with stagnant air might have contributed to this result. The size level was in close agreement with results reported for underground conditions. (Busigin et al, 1981) (Figures 3, 4A & 4D)

The value of σ_g was exceptionally high (12.4) for aerosols suspended in such a stagnant atmosphere. This is an indication of a multi-modal generation of the aerosol inside the pit; these aerosols probably included condensation nuclei from diesel engine emission and attached free atoms of radon daughters. The respirable fraction of radioactive aerosols was 97.5% of the total activity, indicating that the majority of radioactive aerosols are of submicron size.

In the cab environment however, these statistical figures for radioactive aerosol were very different from the values for outdoor. The values of AMAD were 1.3 to 2.0 μm for the backhoe, 1.0 to 1.05 μm for the dumptruck, 1.5 to 2.5 μm for the bulldozer and 3.8 μm for the drill respectively. These figures

are typical of sources created predominantly by mechanical dispersion as exhibited in the particle size spectrum. The respirable fraction of radioactive aerosols was consistently 60 - 75% indicating similar levels to the figures obtained with the total dust. (Table 8)

3. Uranium Ore Dust

The values of AMAD for aerosol particles in the open-pit environment were at 2.0 um indicating close agreement with the values for the total dust. The values of σ_g were 3.5 to 6.5 and in the same range as the total dust. The respirable fraction of radioactive (long-lived) dust was 69 to 77%, indicating that the uranium ore dust had similar characteristics to the total dust. (Table 8, Figures 5A - 5E)

The characteristics of uranium ore dust, which was collected in the equipment cabs, had a similarity to outdoor aerosols. Again, this fact suggests that the uranium ore dust present in the cabs had not entered through the HEPA filters, but was due to the resuspension of once settled dust because the particle size was coarse. This could be further confirmed by comparing mean values of σ_g between the total dust (4.7) and uranium ore dust (4.34). (Table 8)

4. Free Silica Concentration

The concentration of airborne respirable quartz was determined inside and outside the equipment cabs for both uranium ore and waste handling areas. The content of total quartz (respirable and non-respirable quartz), to the total dust (respirable and non-respirable dust), was up to 8% for front-end loader (inside), but the content remained lower than 5% inside most of the equipment. (Table 9)

The values of respirable quartz concentration in various operations fluctuated widely among the types of equipment. For uranium ore mining, the values were up to 5 $\mu g/m^3$ among all the equipment, however a higher concentration of respirable quartz was found in waste handling ranging up to 10 $\mu g/m^3$ inside the cab, while the respirable quartz in outdoor air contained up to 35 $\mu g/m^3$. (Table 10)

5. Particle Morphology

The potential origins of airborne particles inside cabs were; ore dust containing uranium, dust from waste materials containing quartz, exhaust emissions from equipment diesel engines, fragments of pre-filter fibers, fiber

dusts from work clothing and particles from fugitive dust which had penetrated into the cabs. These dust particles have characteristic shapes in the airborne phase.

Dust collected in waste handling operations had a distinctive feature of predominantly light-coloured particles which are assumed to be quartz, rather than dark-coloured particles which are assumed to be uranium containing ores or clay materials of waste. There were signs of flaky but dark-coloured particles in both ore and waste operations indicating the possible presence of soot particles which had penetrated into cabs. These particles, when mounted on a membrane filter, lost their original morphology which is strongly suspected to be a chain aggregate of condensation nuclei. (Wells et al, 1974)

The presence of pyramid shaped, sharp-edged particles showing strong birefringency was observed under a polarized light microscope and these were identified as free silica (quartz) particles. Confirmation by using energy dispersing x-ray analysis with scanning electron microscopy and quantification by infrared spectroscopy, was limited by the insufficient mass of dust collected on stages of the smaller size ranges of the cascade impactor to meet the threshold sensitivity of analytical instruments (10 ug per analytical sample). Only a limited number of samples were sufficient for the analysis to determine respirable quartz concentration of 20 - 25 ug/m^3 range. (Table 10)

K. Cab Surface

1. Air flow Distribution and Pattern

The air flow characteristics in cabs, which also describe the air velocities and air burst frequencies on the various surfaces, indicate the degree and extent to which dust resuspension takes place. A general tendency of air velocity distribution inside the cabs of all the equipment tested is predominantly turbulent at the upper half of the cab confinement.

The air velocity in the shoulder region and in the breathing zone of the operator ranged from 0.03 to 1.02 m/sec., when the air conditioner was set at a low range, and purified air was supplied through the HEPA filter. The air speed went up to 1.78 m/sec at the high setting. However, when the AC system was off and the air flow as only through the HEPA filter, the air velocity inside the cab ranged from 0.01 to 0.1 m/sec. The low range operation of the AC system maintained a rate of air change in the cab which was adequate for the operator's comfort.

The distribution pattern of air velocities over various regions of the cab surface was also affected by the geometry of the cab, and more specifically by the location of the HEPA outlet. The highest air velocities were found on the ceiling for both AC settings with the front-end loader which had the HEPA outlet over the head of the operator (ceiling). (Table 11)

The frequency of air bursts, or air velocity fluctuation as a function of time, inside the cabs, recorded on chart, ranged from 50 to 200 Hz. The mean frequencies for both AC settings varied from region to region of the cab surfaces, being highest at the floor and breathing zone (over 100 Hz) and the lowest at the rear surface (70 Hz level) indicating the effect of surface roughness. (Table 12) By simply assuming that the rate of dust resuspension is a function of air burst frequency, then a higher rate of dust resuspension would be expected from the front and floor region. The rate of resuspension was also affected by the source strength (amount once deposited); therefore a wipe test of these surfaces was necessary in order to evaluate the total resuspension from these surfaces. (Atiemo, 1981)

2. Surface Contamination

Results of the wipe test, over 7 representative surfaces, indicate that the highest radioactive contamination occurred at the dashboard region (mean of 0.101 pCi/cm^2), followed by the right side surface (door, 0.062 pCi/cm^2). The complicated or aerodynamically rough surface of the dashboard must have contributed to this high level of contamination due to the deposition of aerosols by turbulence while the nature of contamination over the (right) door seems different. The right side door is used with most of the equipment for the entry and the contamination would have occurred by direct contact with contaminated surfaces, such as the clothing of a worker at the end of a shift. (Table 13)

Among all of the equipment, the contamination level of the ceiling was lowest (0.008 pCi/cm^2) and this was due to the location of fresh air supplied through the HEPA filter. The above tendency was already demonstrated in a similar study on farm machinery cabs. (Atiemo, 1981)

A difference in surface contamination levels between the equipment assigned exclusively for ore mining and waste handling was expected. Wipe testing showed no distinctive difference in terms of contamination of a unit surface (pCi/cm^2) between the 2 groups. The size of contaminated surfaces

would have been different particularly the contamination due to the direct contact with contaminated sources. Only exception is that high values (over 0.15 pCi/cm^2) were found on a few surfaces of ore handling equipment. (Table 13)

The radioactivity measured in the wipe test samples was only for long-lived radionuclides or uranium ores contained in the dust particles; therefore additional contamination by adhesion of penetrated radioactive gas, which comes through the HEPA filter, over these surfaces must be considered for realistic estimation of surface contamination.

3. Estimation of Dust Resuspension

It is likely that the primary source of dust emission inside the equipment cab was the resuspension of floor dust and that the secondary sources were the resuspension of once-deposited dusts on other surfaces. However, the data produced in this study were still insufficient to make a precise estimation of the resuspension specifically contributed by the secondary sources. At least, the nature of the sources and the mechanisms leading to degradation of the air quality inside the cab may be identified. Heavily contaminated surfaces such as dashboards could become one of the auxiliary sources that require further investigation.

Since the aerosol penetration through the HEPA filter would be negligible under normal circumstances, the presence of radioactive gas inside the cab and subsequent attachment to suspended dust particles could also contribute to the degree of contamination.

L. Worker Exposure Estimation

1. Suspended Particulate Matter

The term "suspended particulate matter" is used by Environment Canada in the concept of air pollution; however ACGIH's TLV for nuisance particulate may be applicable in some circumstances for general work environments like open-pits. The major difference between these 2 standards is the manner in which the concentration of particles is measured. The standard set by Environment Canada is for the general atmospheric environment, while the standard proposed by ACGIH is specified for the breathing zone of workers in work-room environments.

The potential exposure of workers to nuisance particulate is far less than 5 mg/m^3, particularly inside the cabs which remained well below 1 mg/m^3. (Table 4)

2. Radon and its Daughters

Inside the pit, in the vicinity of the mining equipment, the short-term average of radon gas concentration was up to 300 pCi/L, in the morning of September 23, 1980, when the high-grade ore was mined under stagnant atmospheric conditions. (Table 5)

However, the short-term average concentration of alpha activity inside the cabs of the backhoe which was assigned for uranium ore mining fluctuated from 1 to 34 pCi/L. Sometimes the inside level was higher than the outdoor due to the build-up on July 19, 1981. (Table 7A) The concentration of radon gas inside the Foremost dumptruck ranged from 1 to 8 pCi/L and was in general lower than in the backhoe and remained within the MPC. (Table 7B) The levels of radon gas into the bulldozer cab ranged from 1 to 60 pCi/L and fluctuated. A high level of 57.1 pCi/L occurred on August 9, 1981, in the early morning; however this value was only obtained as a short-term average.

The levels of radon gas into the cabs of equipment assigned primarily for waste handling were approximately 1 pCi/L. The above figures suggest that radon gas could have penetrated into the cab through the HEPA filter and tended to build up. (Table 7D)

All sampling activities were conducted under an agreement with the company and with permission of the pit foreman. Therefore the worker exposure to radon daughters was always measured in a routine operation. The great majority of measured short-term average values were within the same order of magnitude as the posted working level. The activity of radon daughters inside the backhoe ranged from 0.002 to 0.094 WL during mining operations of high-grade ores. (Table 7A) The same tendency was found with the Foremost dumptruck ranging from 0.006 to 0.089 WL, with the bulldozer ranging from 0.006 to 0.09 WL (Tables 7B & 7C) and the penetration of radon daughters inside the waste handling equipment remained lower ranging from 0.001 to 0.015 WL, while the outdoor concentration reached 0.032 WL. (Table 7D)

The concentrations of alpha activity of radon and daughters obtained reached 0.1 WL with the backhoe, 0.09 WL with the dumptruck and the bulldozer; however it was up to 0.01 WL for waste handling equipment. The effect of

the job category, or type of equipment assigned, becomes obvious in comparing the values of short-term average of worker exposure. The contribution of high concentrations of radon to the higher values of alpha activity concentration is also apparent.

Annual cumulative exposure of workers to alpha emitters in Cluff Lake, was calculated. (Alderman, 1982) Including mill workers, 78.4% of the total population monitored, were exposed to alpha radiation ranging from 0 to 0.5 WLM, 90% of them were exposed at the range from 0 to 1.0 WLM. By assuming that over a period of mining operations of 6 months workers in open-pit mining are exposed up to 0.5 WLM/year, then they may be exposed to an average of 0.083 WL in every period of 170 working hours per month.

The value of 0.083 WL in this study was exceeded in mining of high-grade ores, in the backhoe, on August 8, 1981, (0.094 WL), in the dumptruck on July 18, 1981, (0.089 WL), and in the bulldozer on July 19, 1981, (0.09 WL). The rest of the exposure episodes during all the site visits resulted in lower values.

3. Uranium Ore Dust

The content of uranium ore in the airborne dust was determined for samples collected in the outdoor environment and inside the cabs. The value was up to 6.7% for the outdoor dust, while the content of uranium ore in the airborne dust, in contrast to the nominal concentration of uranium in the ore, ranged from 0.1% for dumptrucks to 0.3% for the backhoe and bulldozer respectively. Therefore, the mass concentrations of respirable dust inside cabs, though they are short-term average concentration ranging from 0.01 to 1 mg/m^3 may be converted into respirable natural uranium concentration of 0.0002 to 0.02 mg/m^3. The values calculated all remain below the limit of 0.2 mg/m^3 proposed by Labour Saskatchewan. (Table 4)

4. Surface Contamination as Sources of Exposure

Among all wipe samples collected, samples with the highest radioactivity were found in the dashboard region where the highest dust deposition is expected. Even these extreme values still remain up to 0.1 pCi/cm^2 range and never exceed 10 pCi/cm^2 proposed by IAEA. Therefore, the possibility of the cab interior surfaces as important sources of worker exposure by direct contact may be ruled out. (Table 13 and Table 3) (Figures 6A & 6B)

5. Respirable Quartz

The content of quartz in the respirable dust ranged up to 8%. However the majority of samples collected inside the cabs contained about 5% mass of quartz. (Table 9) If the formula of ACGIH's TLV is used, the TLV for dust containing such quartz is 1428 $\mu g/m^3$ of respirable dust or 71.4 $\mu g/m^3$ of respirable quartz in the breathing zone as the 8-hours time-weighted average. Calculated values for both ore and waste handling ranged from 0.7 to 9.4 $\mu g/m^3$ and never exceeded provincial limit of 100 $\mu g/m^3$.

6. Combined Exposure

Combined threshold limit value, consisting of respirable uranium dust and respirable quartz, was calculated according to the ACGIH formula for worker exposure in handling high-grade ore and in waste handling operations. The airborne concentration of respirable dust was grouped in low (0.1 mg/m^3), medium (0.5 mg/m^3) and high range (1.5 mg/m^3) based on the measurements made inside the cabs, within the range of concentrations actually measured inside the cabs.

The content of uranium ore dust in high-grade ore mining remained at 0.3% in the backhoe and bulldozer and 0.1% in the Foremost dumptruck. These values are extremely low as compared to the outdoor concentration of 6.7%. This implies that much of the uranium bearing dust did not penetrate into the cabs through the HEPA filter, but originated from once-deposited surfaces such as dusty floors or other surfaces by resuspension. For the realistic calculation of combined exposure, the higher concentration of uranium dust cannot be used. Those figures obtained in the previous study, are not for airborne dust inside the cab but for outdoor airborne dust (6.7%) and for a high-grade ore body (29.3%). (Cluff Lake B.I., 1978) Thus the value of c/TLV for uranium ore dust by using a TLV of 200 $\mu g/m^3$ ranged from 0.0015 to 0.0035. (Table 14) The TLV respirable quartz was calculated according to the ACGIH formula and the c/TLV for quartz ranged from 0.005 to 0.0029 among all equipment in high-grade ore mining.

In waste handling, the content of uranium ore dust in the respirable size range was assumed at 0.1% for all of the equipment, and the content of respirable quartz was, in general higher at 2 to 8% as compared to 1 to 3% range for high-grade ore mining. The c/TLV was calculated for uranium dust and quartz.

The combined TLV thus calculated for high-grade ore mining and waste handling, did not exceed unity under circumstances that were actually encountered during a series of field measurements. This is mainly due to a unexpectedly low c/TLV for uranium ore dust (0.0001 range) found in high-grade ore mining. The range of combined TLV for the 2 major types of operation did not differ markedly. However the contribution of the c/TLV for quartz was always higher in waste handling operations. (Table 15)

Another study indicates the limiting factor of mixed exposure in uranium mining. (Borak et al, 1982) Airborne dust containing uranium of 1% or higher, becomes a limiting factor of workers' combined exposure regardless of the content of quartz in the dust. However, the content of uranium ore dust in this study was 0.3%. The content of respirable quartz varied from 1 to 3%, therefore, in the range of 0.1 to 0.3% of uranium ore the limiting factor is still predominantly uranium ore dust and followed by quartz containing dust. (Zone B in Figure 7) In waste handling, this limiting factor becomes reversed: that is, quartz containing predominates and supplemented by uranium ore dust (Zone C in Figure 7) due to a high content of quartz in the airborne dust ranging up to 8%.

Conclusions

1. The general area concentration of radon daughters in the open-pit environment ranged from 0.0001 to 0.01 working levels.

2. The ratio of the total dust concentration in the breathing zone of operators equipment cabs to that outdoors ranged from 10 to 80%.

3. The short-term average concentration (15 minutes) of radon gas in the open-pit environment ranged from 25 to 300 pCi/L while a backhoe was mining high-grade ore on a cool morning.

4. In the mining high-grade ore, the levels of radioactive aerosols in cabs of the backhoe and the dumptruck ranged from 0.001 to 0.1 WL. The levels of radon gas ranged from 1 to 30 pCi/L in the backhoe, from 1 to 5 pCi/L in the dumptruck, and from 1 to 50 pCi/L in the bulldozer as short-term averages.

5. The levels of radioactive aerosols into equipment cabs in waste handling ranged from 0.001 to 0.1 WL as 15 minutes averages.

6. No thoron gas was detected in the mine environment during the period of September 22, 23 and 24, 1980.

7. The particle size distributions of aerosols in the cabs were very similar to the values obtained for the outdoor environment.

8. The activity median aerodynamic diameter of the attached radon daughters in the mining environment in the vicinity of the mining equipment was 0.03 μm showing close agreement with values obtained in underground conditions.

9. Activity median aerodynamic diameter of uranium ore dust was about 2.0 μm both inside the cabs and in the outdoor environment. The activity median aerodynamic diameter of radioactive aerosol in the cabs was similar to that of uranium ore dust in the cabs.

10. The concentration of free silica inside all equipment cabs remained at 2 to 8% of the total airborne dust.

11. Inside mining equipment cabs the surface contamination with uranium ore dust reached 0.3 pCi/cm^2, and was highest in the dashboard region and lowest for the ceiling region. It remained far less than the safety standard of 10 pCi/cm^2. There was distinctive difference between the contamination levels in the various types of equipment used.

12. Resuspension of dust from the floor and other contaminated surfaces is the most likely explanation for the major part of the airborne dust in the cabs.

13. The combined TLV derived from the ACGIH standards and calculated for a mixture of uranium ore dust and respirable quartz did not exceed unity in both ore mining and waste handling. The presence of uranium ore at such concentration in the mixture was the limiting factor in determining such combined exposure. This did not take into account, exposure to radon and its daughters, or possible combined effects between radiation and quartz exposure.

Recommendations

1. It is recommended that the floor of the equipment cab should be kept clean. It is recommended to install an easy-to-clean floor by having an elevated screen under which a removable tray catches all of the dust.

2. It is recommended to carry out decontamination of the internal cab surface, in particular the dashboard region, at regular intervals.

3. It is recommended to install a magneheric gauge with a warning signal inside cabs, so that an operator may be able to detect an accidental leak or depressurization by breakdown of the air supply duct.

4. Dust concentration in air equipment cabs should be minimized by an adequate supply of clean air, and by keeping doors and windows closed even when the equipment is standing idle. (CSA, 1980)

5. Further studies are advised regarding the aerodynamic and human engineering aspects of equipment cabs to minimize worker exposure to alpha emitters through inhalation.

6. The present report was unavoidably based on a limited number of observations, the timing of which was expected by workers and management. Valid worker exposure measurements which would allow worker safety to be evaluated are recommended. These would require unexpected radon and other measurements to be carried out in a variety of circumstances and in a greater number of instances over a period of time as the equipment ages.

7. Standards for combined exposure of workers to radioactive and other aerosols such as quartz and to radon gas should be developed.

Acknowledgments

The advice and assistance provided by Dr. H. Stocker of AECB, Mr. J. Alderman of Labour Saskatchewan, Dr. F. Fried of the Saskatchewan Health Research Board and Mr. T. Meadley of the Cluff Lake Mining Company Ltd., are gratefully acknowledged. Sincere thanks to the D-pit supervisors for providing facilities and conveniences for field sampling activities and to Dr. R. Marchant of the Saskatchewan Mining Development Corporation for data interpretation. Special thanks to Dr. V.L. Matthews, Professor and Head of the Department of Social and Preventive Medicine for the general supervision and to K. Wallace, M. Peters and all of the summer students of the Saskatchewan Research Council for field work assistance, and for the typing service of this report by Miss Barbara Sherstobitoff of the Department of Social and Preventive Medicine.

REFERENCES

AERE: Health Physics Handbook. Area and material decontamination. General Dynamics. OSP - 379, 1963.

Alderman, J.R.: Occupational Health and Safety of Workers in Saskatchewan Uranium Mines. Proc. Int's conf. Radiation Hazards in Mining. pp 608-615, 1982.

American Conference of Governmental Industrial Hygienists: "Threshold Limit Values for Chemical Substance in Workroom Air". 1981.

Atiemo, M.A., Yoshida, K., Zoerb, G.C.: Dust Measurement in Tractor and Combine Cabs. Transactions of A.S.A.E., pp 571-576, 1980.

Atiemo, M.A.: The Deposition and Resuspension of Dust in Protective Cabs of farm Tractors. PhD thesis, University of Saskatchewan. Saskatoon, Saskatchewan, 1981.

Budnitz, R.F.: Radon - 222 and its daughters - A review of instrumentation for occupational and environmental monitoring. Health Physics, 26: 145-163, 1974.

Busigin, A., Van der Vooren, A., Phillips, C.R.: Measurement of the Total and Radioactive Aerosol Size Distributions in a Canadian Uranium Mine. Jr. of the Amer. Industrial Hygiene Assc. 42: 310-314, 1981.

Can. Standard Assn.: Rollover protective structure of agriculture and construction, earth moving forestry, industrial and mining machines. CSA Standard 13352 - M1980. 1980.

Cluff Lake Board of Inquiry: Final Report pp 429. Chapter III. Radioactive and the biological effects of radiation with reference to existing standards. 1978.

Cross, F.T., et al: Inhaled Radon daughters and Uranium ore dust in Rodents. Battelle Pacific Northwest Lab. Ann. Report. pp 3: 55-57, 1978.

Environment Canada: "Criteria for National Air Quality Objectives". Sub-Committee Report on Air Quality Objectives. Nov. 1976.

Fry, R.M.: Radiation Hazards in Uranium Mining and Milling. Atomic Energy, October: 12-31, 1975.

ICRP: Occupational Limits for Inhalation of Radon - 222, Radon - 220 and their short-lived daughters. Pub. 32 (Jacobi, W. The new ICRP recommendations on occupational limits for radon daughters). Proc. Int'l. Conf. Radiation Hazards in Mining. pp 503-510, 1981.

International Atomic Energy Agency: "Manual on Radiological Safety in Uranium and Thorium Mines and Mills". Safety Series No. 45 Vienna, 1976.

Key Lake of Inquiry: Final Report, Chapter 6, Evaluation of Certain Filters. pp 11: 88-96, 1980.

Kreb, H.A., Thompson, J.E.: "Tractor Cab Cooling Requirements". S.A.E. paper No. 71-0692. 1971.

Leach, V.A., et al: Measurement of Radiation Parameters in open-cut mining situations. Proc. Int. Conf. Rad. Hazards in Mining, pp 465-470, 1982.

Miller, H.T.: Radiation exposures associated with surfaces Mining of Uranium. Health Physics. 32: 523-527, 1977.

NIOSH: Occupational exposure sampling strategy manual. DHEW (NIOSH) pub. No. 77-173, 1977.

NIOSH: Occupational exposure to crystalline silica. DHEW (NIOSH) pub. No. 75-120, 1975.

NIOSH: Criteria for a recommended standard - Occupational Exposure to Crystalline Silica. 1974.

Labour Saskatchewan: The Occupational Health and Safety Act, Section 13, Saskatchewan Regulations 55/81. March, 1981.

Wells, O.C., Boyde, A., Lifshin, E., Rezanowich, A.: "Scanning Electron Microscopy". McGraw Hill, 1974.

Yoshida, K.: "Laboratory Test of Candidate Filter Packages Intended for Use with Equipment Cab in Open Pit Mining of Uranium". Pub. No. P-781-1-E-81, Sask. Research Council, 1981.

Table 1. Physical Condition of Ambient Air - Cluff Lake

Date	Max. Air Temp (°C)	Relative Humidity (%)	Mean Wind Speed (km/h)	Remarks
Site Visit No.1 (1980)				
Sept. 22	15	70	2	snow flurries
23	20	80	5	wet
24	25	70	4	wet
25	20	65	2	sunny
26	20	60	2	cloudy
27	25	60	5	sunny breaks
28	25	40	4	light rain
Site Visit No.2 (1980)				
Oct. 6	20	45	2	warm, dry
7	30	60	2	hot, dry
8	30	50	40	cloudy, windy
9	25	50	25	dry, windy
10	25	50	17	warm, dry
Site Visit No.3 (1981)				
July 16	30	35	5	hot, dry
17	25	35	30	hot, dry, windy
18	30	60	10	hot, dry
19	20	40	15	sunny
Site Visit No.4 (1981)				
Aug. 5	30	40	2	hot, dry
6	25	40	25	sunny, dry, windy
7	25	45	17	hot, dry, windy
8	25	55	2	sunny, clear
9	25	40	12	warmer, windy
10	20	60	5	warmer
11	20	60	30	cool, windy

Measurements were made periodically in the vicinity of the equipment.

Table 2. Recommended Maximum Permissible Contamination Levels (Removable)

Type of Surface	Alpha Activity fixed (pCi/cm^2)
Body surfaces	10
Personal clothing	10
Protective clothing	50
Inactive areas and low and medium level laboratories	10

University of Saskatchewan - Radiation Safety Standard, 1981

Table 3. Action Required for Removal of Surface Contamination

Alpha Activity pCi/cm^2	Action
Less 0.2	No immediate action needed, but should be cleaned as soon as possible.
0.2-1.0	Area or surface shall be cleaned as soon as possible by authorized user.
1.0-5.0	Immediate action shall be taken by authorized user to decontaminate. Shoe covers and step-off pads may be required.
Over 5.0	Prevent entry into the room or area until safety officer evaluates situation.

Condition: Medium level laboratories.

University of Saskatchewan - Radiation Safety Standard, 1981

Table 4. Summary of Total Dust Concentration

	Foremost D. Truck(a)	Foremost D. Truck(b)	Wabco Dumptruck(a)	Wabco Dumptruck(b)	Bulldozer		Front-end Loader	
	July 17, 1981	July 16, 1981	July 17, 1981	July 17, 1981	Oct. 7, 1980	Oct. 7, 1980	July 17, 1981	
	1:20-5:35 pm	10:20-4:55 pm	1:00-5:15 pm	1:00-5:25 pm	10:45-5:00 pm	1:00-5:12 pm	1:00-5:45 pm	
nside on	0.19	0.07	0.40	0.99	0.13	0.16	1.12	
tdoor	1.20	0.40	1.25	1.25	0.47	1.33	1.37	
loor	0.16	0.18	0.32	0.79	0.28	0.12	0.82	

Table 5. Radon Concentration inside Pit (outdoor environment)

Sampling ended at	Sampling Period (Min)	Radon Concentration (pCi/L)	Operation
10:00 a.m.	30	85.6	In the vicinity of
10:30	30	40.2	backhoe while mining
11:00	30	26.4	high-grade ores.
11:30	30	31.4	September 23, 1980.
12:00	30	291.7	

Table 6. Summary of Spectrometric Measurements of Radioactivity

Date	Time	Location	Daughters of Rn	Daughters of Th	RaA	RaB	RaC	ThB	ThC	Remarks
Sept. 22, 1980	2:36 p.m.	bottom of pit	0.003	0.000	304	9	17	6	7	snow flurries
	4:09 p.m.	bottom of pit	0.000	0.000	12	7	28	2	0	
Sept. 23, 1980	8:45 a.m.	outdoor	0.003	0.000	31	15	58	2	7	wet, cool
Sept. 24, 1980	8:45 a.m.	outdoor	0.001	0.000	123	30	167	4	23	wet, warmer
	4:20 p.m.	inside (foremost) D. truck	0.001	0.000	27	12	39	2	3	
	5:33 p.m.	inside (foremost) D. truck	0.001	0.000	61	5	22	0	0	
Measuring Unit			Gross alpha (WL)		Total Count of Daughters (cpm)					

Instrument: Pylon WL 1000B alpha spectrometer (instantaneous read-out working level meter)

Operation: High-grade ore mining

Table 7A. Radon and Daughters Present in Backhoe Cab

Date	Sampling Started	Radon (pCi/L)	Daughters (WL)	Environmental Condition and Material Handled
INSIDE CAB				
Sept. 25/80	9:40 a.m.	14.75	0.021	Cool and moist air High-grade ore mining
	2:35 p.m.	8.94	0.011	Slight rain High-grade ore mining
Sept. 26	10:30 a.m.	1.12	0.005	Cool air High-grade ore mining
Sept. 27	3:55 p.m.	1.57	0.009	Cloudy and colder Low-grade ore mining
July 18/81	2:55 p.m.	30.20	0.030	Hot and dry Low-grade ore mining
	2:55 p.m.	10.70	0.042	Hot and dry Low-grade ore mining
July 19	3:30 p.m.	30.00	0.030	Cool and windy Predominantly high-grade ore mining
	3:30 p.m.	12.95	0.027	Cool and windy Predominantly high-grade ore mining
Aug. 7	3:45 p.m.	4.40	0.002	Cool and dry air Predominantly waste handling
Aug. 8	2:20 p.m.	8.30	0.015	Hot and dry air Low-grade ore mining
	8:30 a.m.	33.80	0.094	Hot and dry air Low-grade ore mining
OUTDOOR				
July 18/81	9:25 a.m.	10.60	0.025	Hot and dry air Low-grade ore mining
	2:55 p.m.	9.50	0.020	Hot and dry air Low-grade ore mining

Table 7B. Radon and Daughters Present in Foremost Dumptruck Cab

Date	Sampling Started	Radon (pCi/L)	Daughters (WL)	Environmental Condition and Material Handled
INSIDE CAB				
Sept. 25/80	11:30 a.m.	7.67	0.021	Cool and slight rain High-grade ore mining
	2:15 p.m.	6.67	0.014	Cool and moist air High-grade ore mining
Sept. 27	9:30 a.m.	2.95	0.018	Cloudy and colder Low-grade ore mining
	11:10 a.m.	2:30	0.007	Cloudy and colder Low-grade ore mining
	11:15 a.m.	1.00	0.018	Cloudy and colder Low-grade ore mining
July 18/81	2:45 p.m.	5.66	0.089	Hot and dry air Low-grade ore mining
July 19	2:45 p.m.	1.60	0.025	Cool and windy Predominantly high-grade ore mining
Aug. 8	4:45 p.m.	7.90	0.006	Sunny, windy High-grade ore mining
	2:45 p.m.	-	0.007	Sunny, windy High-grade ore mining
OUTDOOR				
July 18/81	2:45 p.m.	45.60	0.050	Hot and dry air Low-grade ore mining
	1:55 p.m.	-	0.066	Hot and dry air Low-grade ore mining
July 19/81	2:45 p.m.	2.38	0.042	Hot and dry air Low-grade ore mining

Table 7C. Radon and Daughters Present in Bulldozer Cab

Date	Sampling Started	Radon (pCi/L)	Daughters (WL)	Environmental Condition and Material Handled
INSIDE CAB				
Sept. 26/80	9:45 a.m.	12.51	0.021	Cool air High-grade ore mining
	2:30 p.m.	0.85	0.012	Cool air High-grade ore mining
Sept. 27	2:35 p.m.	8.59	0.044	Cloudy and colder Low-grade ore mining
July 19/81	3:30 p.m.	-	0.090	Cool and windy Predominantly high-grade ore mining
Aug. 9	7:55 a.m.	57.10	0.010	Warm, dry air High-grade ore mining
	2:00 p.m.	5.20	0.010	Warm, dry air High-grade ore mining
OUTDOOR				
July 16/81	4:45 p.m.	-	0.006	Hot and dry air Waste handling only
July 19	3:30 p.m.	-	0.080	Cool and windy Predominantly high-grade ore mining

Table 7D. Radon and Daughters Presence in Other Equipment

Date	Sampling Started	Radon (pCi/L)	Daughters (WL)	Environmental Condition and Material Handled
INSIDE CAB				
Aug.11/81	11:15 a.m.	1.18	0.003	Drill, cool and windy, Waste handling
July 16	5:50 p.m.	-	0.001	Front end loader Hot and dry Waste handling only
	4:40 p.m.	-	0.015	Wabco Dumptruck Hot and dry Waste handling only
	4:40 p.m.	-	0.008	Wabco Dumptruck Hot and dry Waste handling only
OUTDOOR				
July 16/81	4:40 p.m.	-	0.032	Wabco Dumptruck Hot and dry Waste handling only

Table 8. Summary of Statistical Parameters in Particle Size Distribution

Equipment	Outdoor	Backhoe	Foremost D. Truck	Bulldozer	Drill
Total Dust					
Date (M/D/Y)	9/27/80-7/19/81	8/7/81	-	8/6/81	
MMAD (μm)	0.6, 3.3	1.8	-	2.3	
Sigma-g	3.8, 8.5	5.3	-	4.2	
Respirable mass (%)	62, 83	73	-	71	
Radon Daughters					
Date (M/D/Y)	8/9/81	8/8/81-8/8/81	8/8/81-8/8/81	8/9/81-8/9/81	8/10/81
AMAD (μm)	0.03	1.3, 2.0	(a)1.0, 1.10(b)	1.6, 2.5	3.8
Sigma-g	12.4	4.0, 6.0	8.2, 8.9	3.6, 7.9	3.7
Respirable mass (%)	98	76, 74	72, 79	66, 82	60
Uranium Ore Dust					
Date (M/D/Y)	8/9/81-8/25/80	8/8/81-8/8/81	8/8/81-8/8/81	8/9/81-8/9/81	8/10/81
AMAD (μm)	2.0, 2.0	1.4, 1.2	(a) 1.5, 2.5(b)	1.5, 2.4	2.7
Sigma-g	3.5, 6.5	4.1, 5.9	3.2, 3.6	4.0, 5.8	3.7
Respirable mass (%)	69, 77	76, 80	70, 88	66, 80	68

Table 9. Quartz Content of Total Airborne Dust (%)

Operation	Uranium Ore Mining		Waste Handling	
Equipment	Inside Cab	Outside	Inside Cab	Outdoor
Backhoe	1.3	2.0	-	-
Dumptrucks	2.1	4.9	2.2	1.9
Bulldozer	2.8	4.0	4.6	4.8
Front End Loader	-	-	7.9	4.0
Drill	-	-	3.9	1.0

Samples collected October 7, 1980 at the bottom of the D-pit.

Table 10. Respirable Quartz Concentration in Various Operations ($\mu g/m^3$)

Operation	Uranium Ore Mining		Waste Handling	
	Inside Cab	Outdoor	Inside Cab	Outdoor
Backhoe	0.71	0.87	-	-
Dumptrucks	3.57	12.30	9.40	3.80
Bulldozer	2.10	25.40	2.99	36.00
Front End Loader	-	-	4.43	6.20
Drill	-	-	3.60	3.70

Respirable mass fraction of quartz is about 50% of the total quartz.

Table 11. Air Velocity Distribution Inside Cab (m/sec)

Cab Region	AC Range	Breathing Zone	Dash-board	Rear	Right	Left	Ceiling	Floor
Backhoe	Low	0.38-0.51	0.13-0.25	0.51-0.76	0.76-1.02	0.25-0.38	0.51-0.78	0.13-0.25
	High	0.40-0.60	0.51-0.76	0.51-0.80	1.02-1.27	0.40-0.51	1.02-1.27	0.25-0.38
Foremost Dumptruck	Low	0.03-0.13	0.03-0.13	0.25-0.38	0.03-0.13	0.51-0.76	0.13-0.25	0.03-0.10
	High	0.03-0.15	0.03-0.15	0.51-0.76	0.76-1.02	0.25-0.38	1.27-1.60	0.03-0.13
Bulldozer	Low	0.25-0.38	0.51-0.76	0.13-0.25	0.25-0.76	0.25-0.38	0.38-0.51	0.03-0.13
	High	0.76-1.02	0.76-1.20	0.13-0.30	0.30-0.80	0.51-0.76	0.40-0.55	0.25-0.38
Front End Loader	Low	0.13-0.25	0.76-1.02	0.25-0.38	1.78-2.03	0.25-0.38	2.03-2.29	0.25-0.38
	High	0.25-0.38	0.80-1.02	0.38-0.51	0.76-1.02	0.46-1.02	2.29-2.54	0.51-0.76
Wabco Dumptruck	Low	0.76-1.02	0.25-0.38	0.38-0.51	0.25-0.38	0.13-0.25	0.13 0.25	0.03-0.13
	High	1.60-1.78	0.51-0.76	0.51-0.76	0.76-1.02	0.25-0.38	0.25-0.38	0.13-0.25

Table 12. Air Burst Frequencies Inside Cabs (Hz)

Cab Region	AC Range	Breathing Zone	Dash-board	Rear	Right	Left	Ceiling	Floor
Backhoe	Low	91	46	75	125	83	92	153
	High	115	54	100	132	118	70	151
Foremost Dumptruck	Low	76	189	76	76	122	76	150
	High	115	106	72	71	125	71	163
Bulldozer	Low	128	106	81	114	106	50	100
	High	150	100	102	108	106	50	78
Front End Loader	Low	125	104	122	107	125	112	127
	High	104	75	85	100	104	138	76
Mean Frequency		113.00	97.50	73.12	91.62	98.62	82.37	124.75

Table 13. Surface Contamination of Equipment Cab (Wipe Test) (pCi/cm^2)

Cab Region	Windshield Region	Right Side	Left Side	Rear Side	Ceiling Region	Dashboard Region	Air Supply Duct
A. Ore Handling							
Backhoe	0.005	0.005 0.008	0.003 0.028	0.005 0.008	0.018	0.061 0.193*	-
Foremost Dumptruck	0.003	0.081	0.023 0.041	0.005 0.020	-	0.036 0.102	-
Bulldozer	0.005	0.061 0.266*	0.003 0.008	0.003 0.063	0.008	0.058 0.140*	0.140
B. Waste Handling							
Front End Loader	0.005 0.010	0.147*	0.030	0.013 0.102	0.003 0.015	0.127	0.050
Wabco Dumptruck	0.038 0.074	0.005 0.015	0.056	0.023 0.071	0.003 0.008	0.061 0.157*	-
Drill	0.008	0.015 0.025	0.005 0.015	0.003 0.025	0.005	0.071	0.012
C. Mean	0.018	0.062	0.021	0.028	0.008	0.101	0.067

* Higher Values

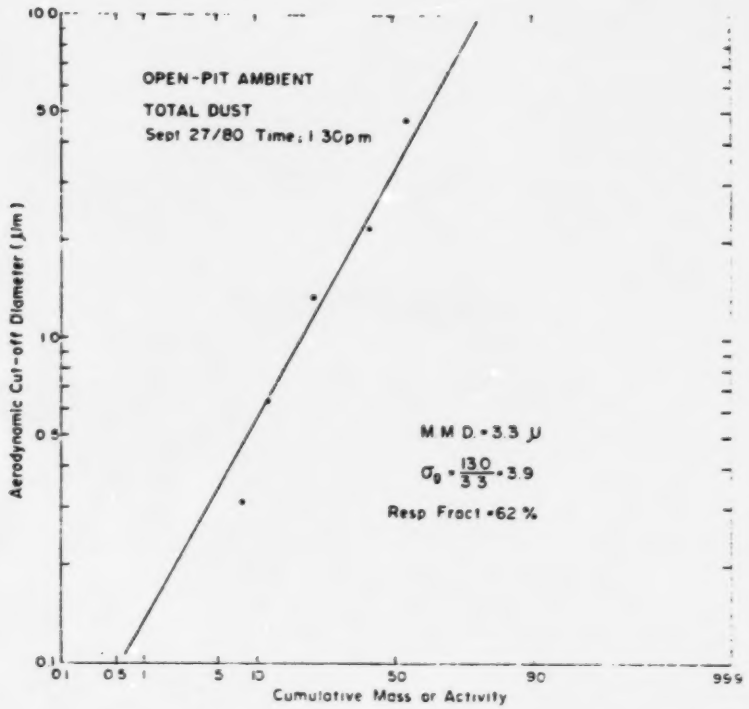
Table 14. Calculation of Combined Exposure (Ore Mining)

Equipment	Resp. Dust conc.(mg/m^3)	U. ore conc.(%)	U. ore conc. ($\mu g/m^3$)	c/TLV	Resp. Quartz conc. (%)	Resp. Quartz conc. ($\mu g/m^3$)	Resp. Quartz TLV (mg/m^3)	c/TLV	Combined TLV
Backhoe	0.1	0.3	0.3	0.0015	1.3	0.71	1.52	0.0005	0.023
	0.5	0.3	1.5	0.0075	1.3	0.71	1.52	0.0005	0.024
	1.5	0.3	4.5	0.0225	1.3	0.71	1.52	0.0005	0.025
Foremost Dumptruck	0.1	0.1	0.1	0.0005	2.1	3.57	1.22	0.0029	0.149
	0.5	0.1	0.5	0.0025	2.1	3.57	1.22	0.0029	0.150
	1.5	0.1	1.5	0.0075	2.1	3.57	1.22	0.0029	0.151
Bulldozer	0.1	0.3	0.3	0.0015	2.8	2.10	1.04	0.0020	0.103
	0.5	0.3	1.5	0.0075	2.8	2.10	1.04	0.0020	0.104
	1.5	0.3	4.5	0.0225	2.8	2.10	1.04	0.0020	0.105

Table 15. Calculation of Combined Exposure (Waste Handling)

Equipment	Resp. Dust (mg/m^3)	Uranium ore* dust ($\mu g/m^3$)	c/TLV	Resp. Quartz conc. (%)	Resp. Quartz conc. ($\mu g/m^3$)	Resp. Quartz TLV (mg/m^3)	c/TLV	Combined TLV
Front End Loader	0.1	0.1	0.0005	7.9	4.43	0.69	0.0064	0.057
	0.5	0.5	0.00025	7.9	4.43	0.69	0.0064	0.056
	1.5	1.5	0.0007	7.9	4.43	0.69	0.0064	0.056
Dumptruck (Wabco)	0.1	0.1	0.0005	2.2	9.40	1.19	0.0079	0.180
	0.5	0.5	0.0025	2.2	9.40	1.19	0.0079	0.182
	1.5	1.5	0.0007	2.2	9.40	1.19	0.0079	0.180
Bulldozer	0.1	0.1	0.0005	4.6	2.99	0.76	0.0039	0.043
	0.5	0.5	0.00025	4.6	2.99	0.76	0.0039	0.043
	1.5	1.5	0.0007	4.6	2.99	0.76	0.0039	0.043
Drill	0.1	0.1	0.0005	3.9	3.60	0.85	0.0042	0.055
	0.5	0.5	0.00025	3.9	3.60	0.85	0.0042	0.055
	1.5	1.5	0.0007	3.9	3.60	0.85	0.0042	0.055

* By assuming that 0.1% of respirable dust is uranium ore dust.



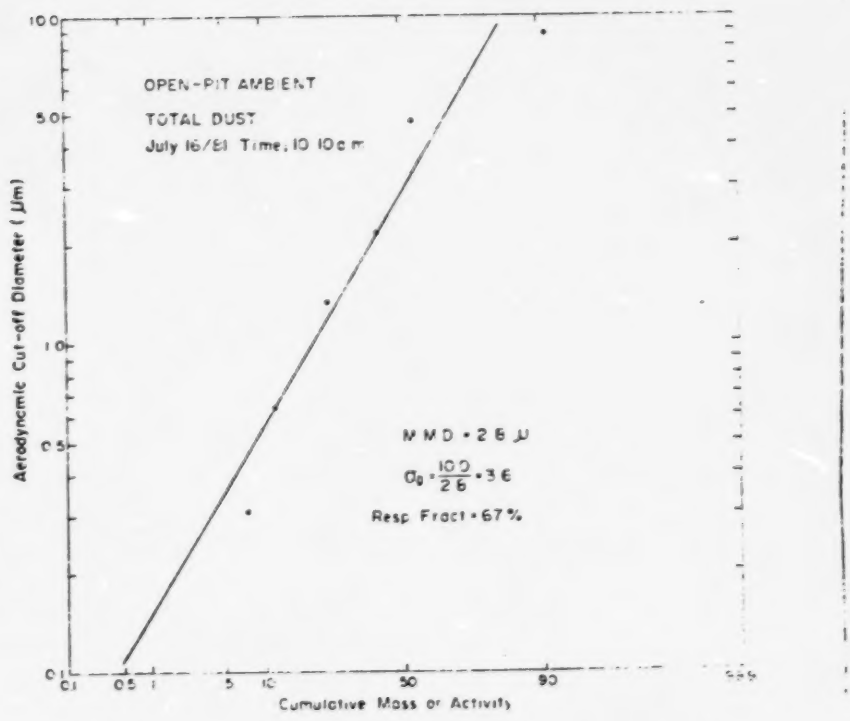


Figure 1. A & B - Particle Size Distribution of Total Dust in Open-Pit Environment (1980 - 1981)

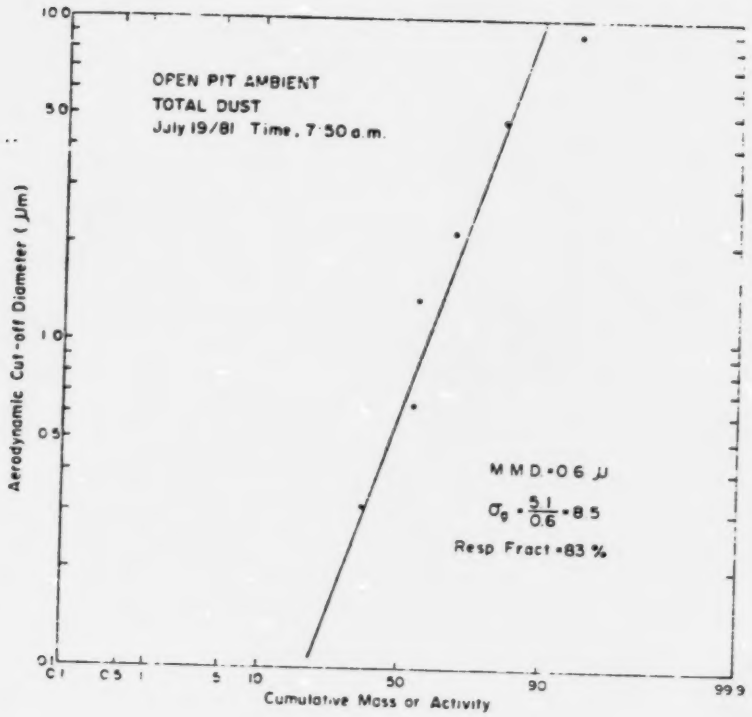
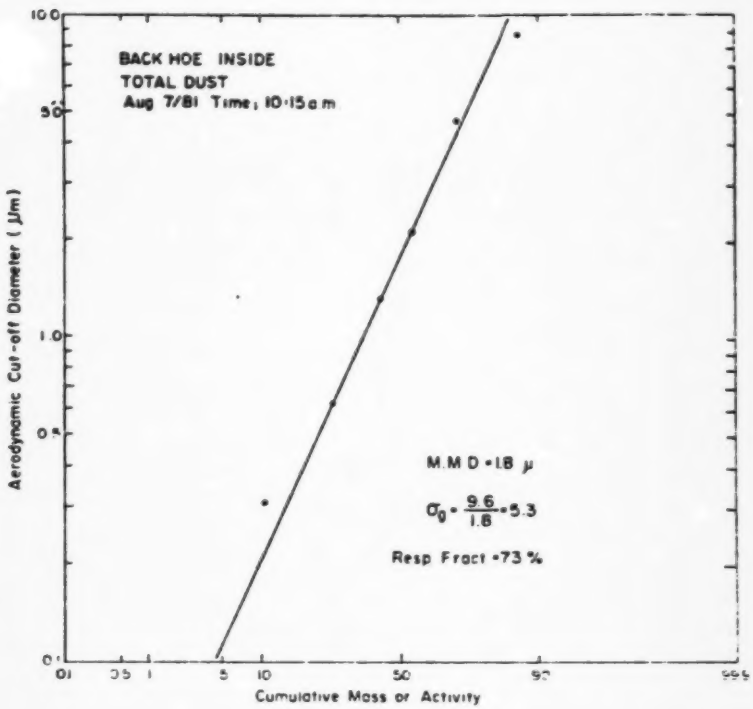


Figure 1 C - Particle Size Distribution of Total Dust in Open-Pit Environment (Calm morning, 1981)



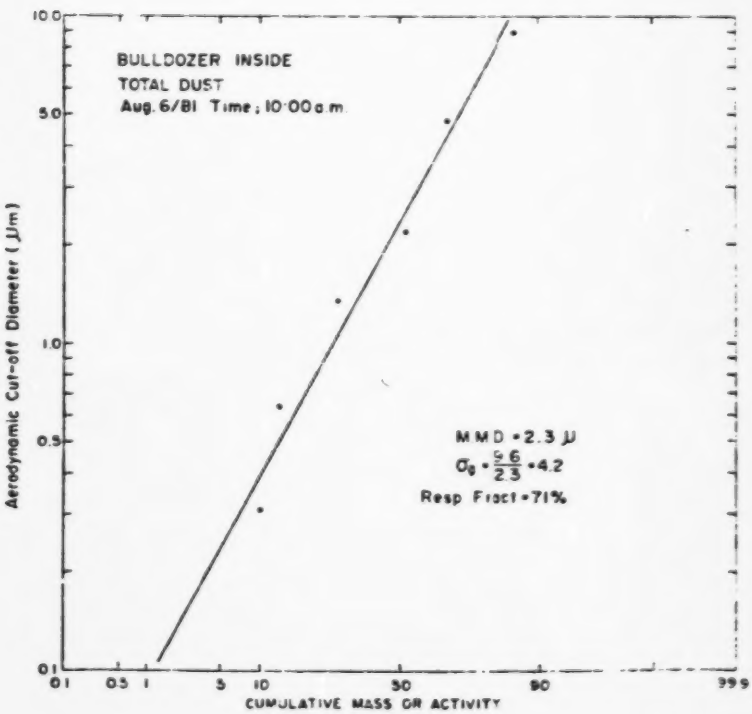


Figure 2 A&B - Particle Size Distribution of Total Dust Inside Cab of Backhoe and Bulldozer

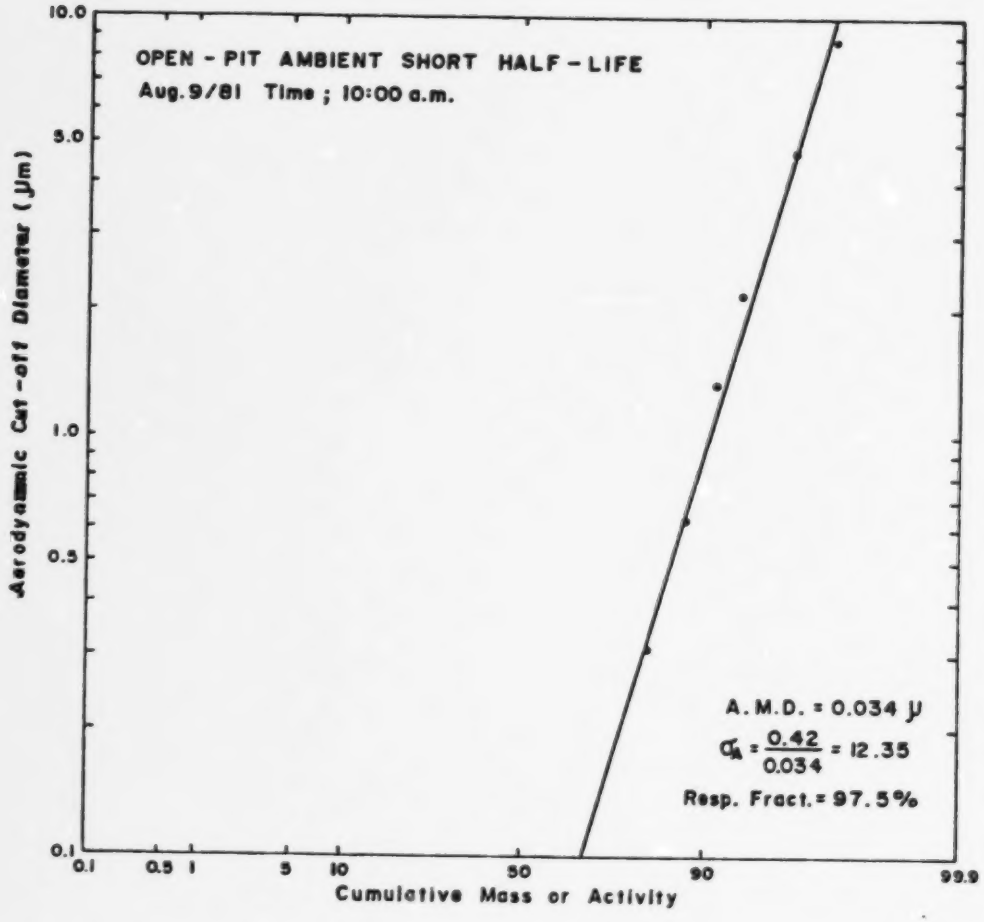
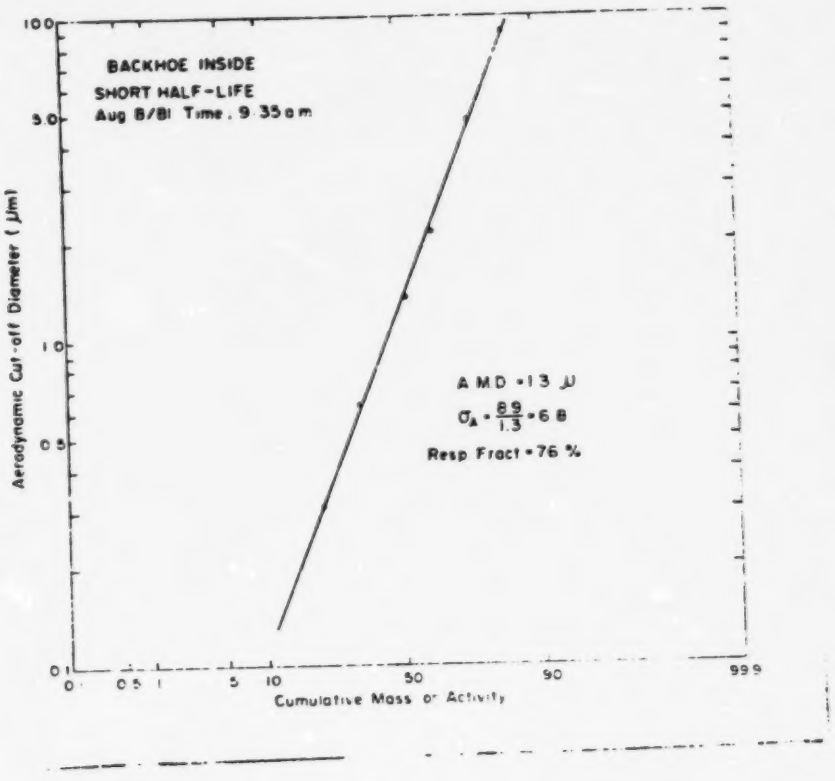


Figure 3. Particle Size Distribution of Aerosols with short half-life Radionuclides in Open-pit Environment (1981)



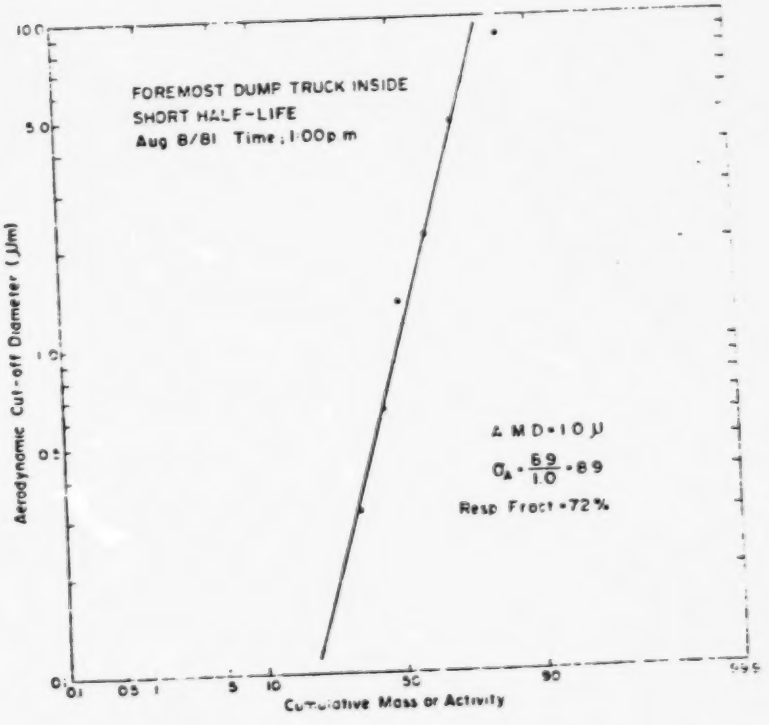
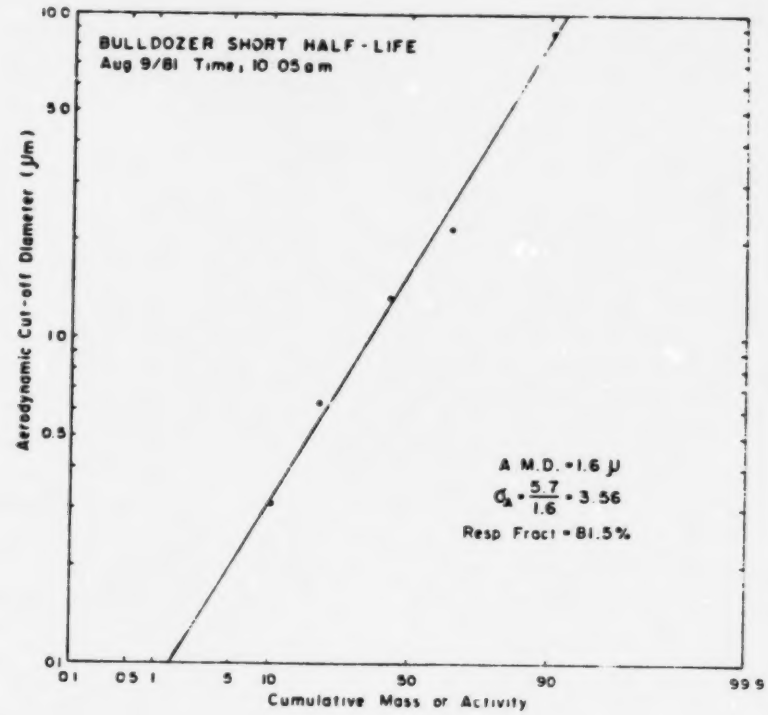


Figure 4 A&B. Particle Size Distribution of Aerosols with short half-life Radionuclides in Cab of Backhoe and Dumptruck



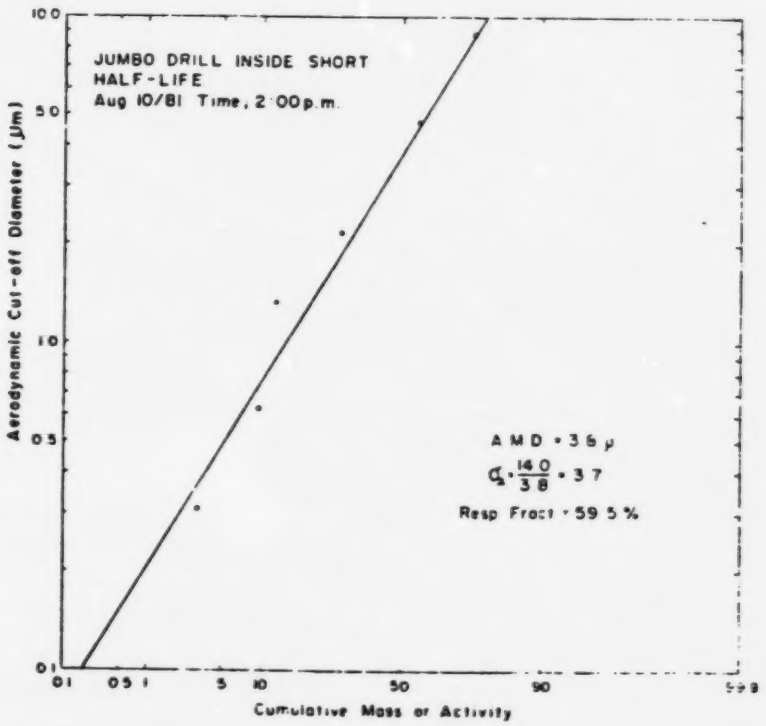


Figure 4 C&D. Particle Size Distribution of Aerosols with short half-life Radionuclides in cab of Bulldozer and Drill

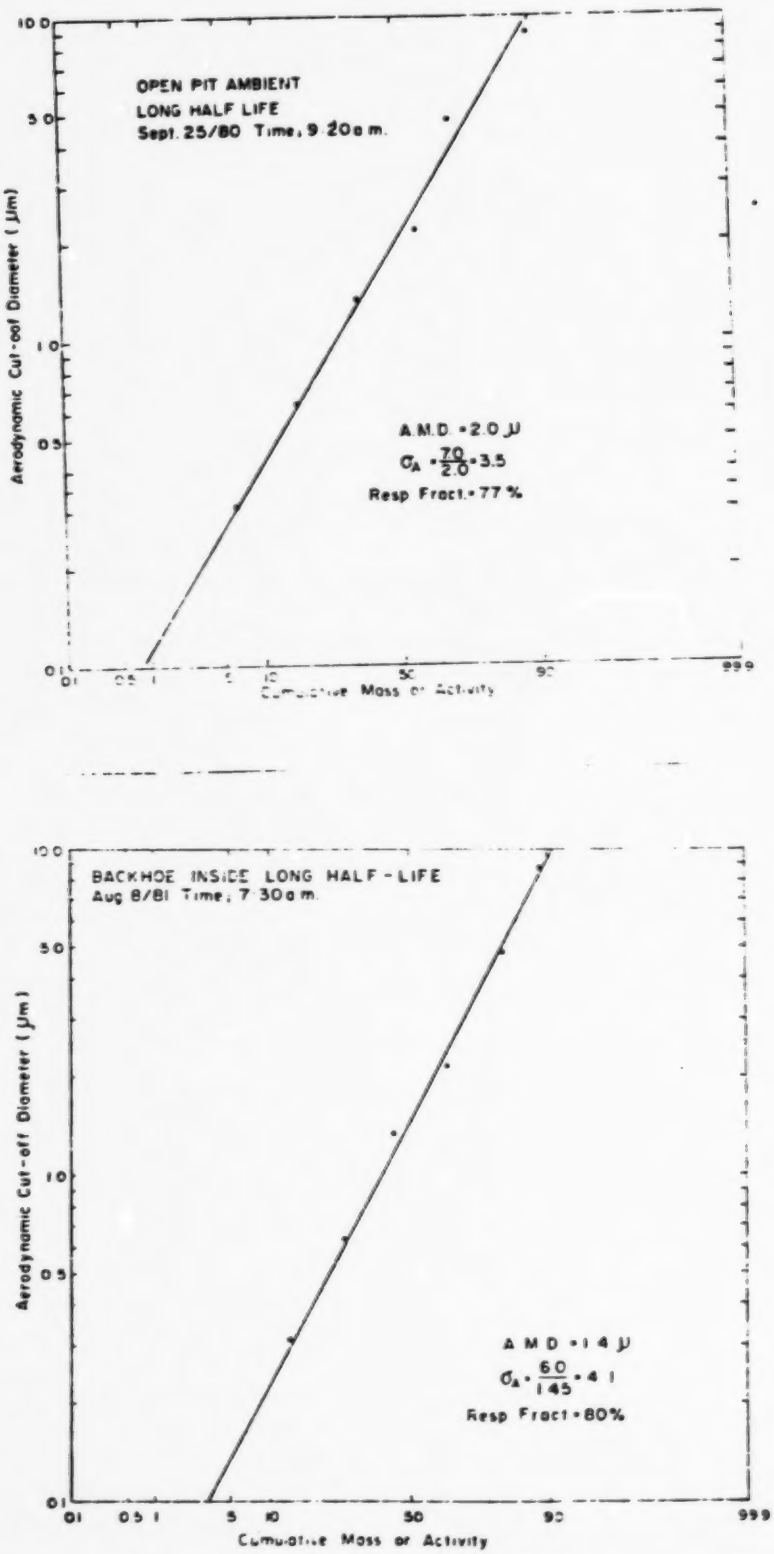
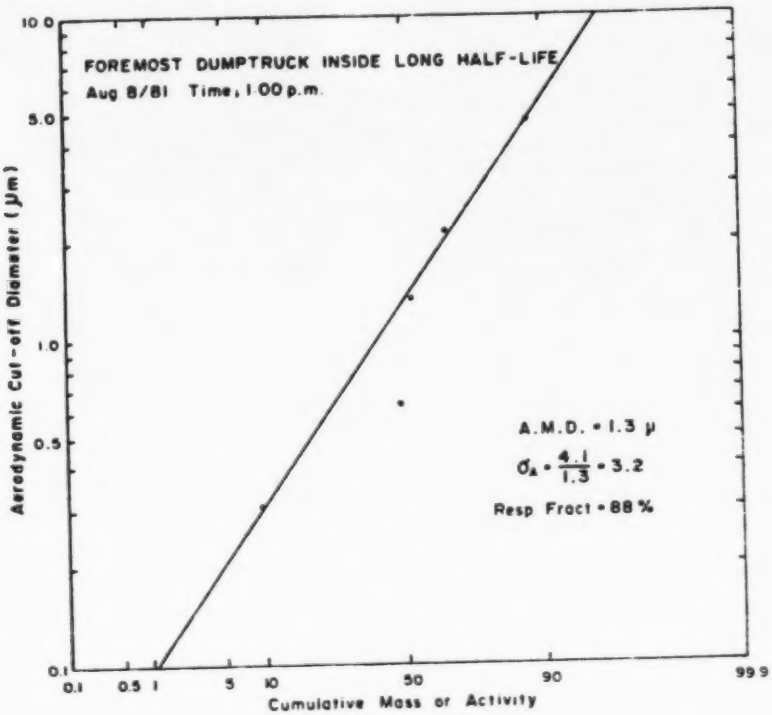

OPEN PIT AMBIENT
LONG HALF LIFE
Sept. 25/80 Time, 9 20 a m.
A.M.D. = 2.0 μ
σA = 70/2.0 = 3.5
Resp Fract. = 77 %
Aerodynamic Cut-off Diameter (μm)
Cumulative Mass or Activity
BACKHOE INSIDE LONG HALF-LIFE
Aug 8/81 Time, 7 30 a m.
A M D = 1 4 μ
σA = 60/145 = 4 1
Resp Fract = 80%
Aerodynamic Cut-off Diameter (μm)
Cumulative Mass or Activity

Figure 5 A&B. Particle Size Distribution of Uranium Ore Dust in Open-pit Environment and Backhoe Cab.



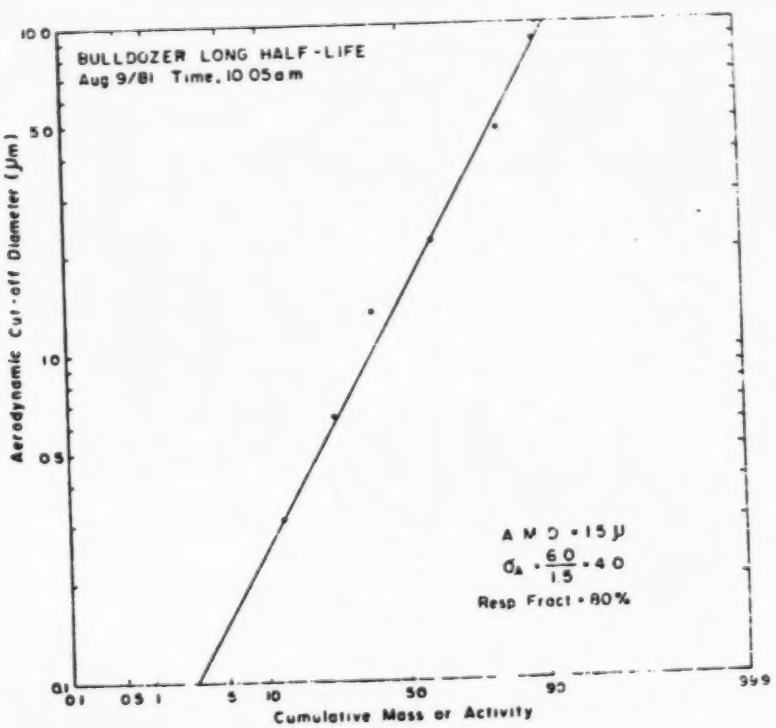


Figure 5 C&D. Particle Size Distribution of Uranium Ore Dust in Cab of Dumptruck and Bulldozer

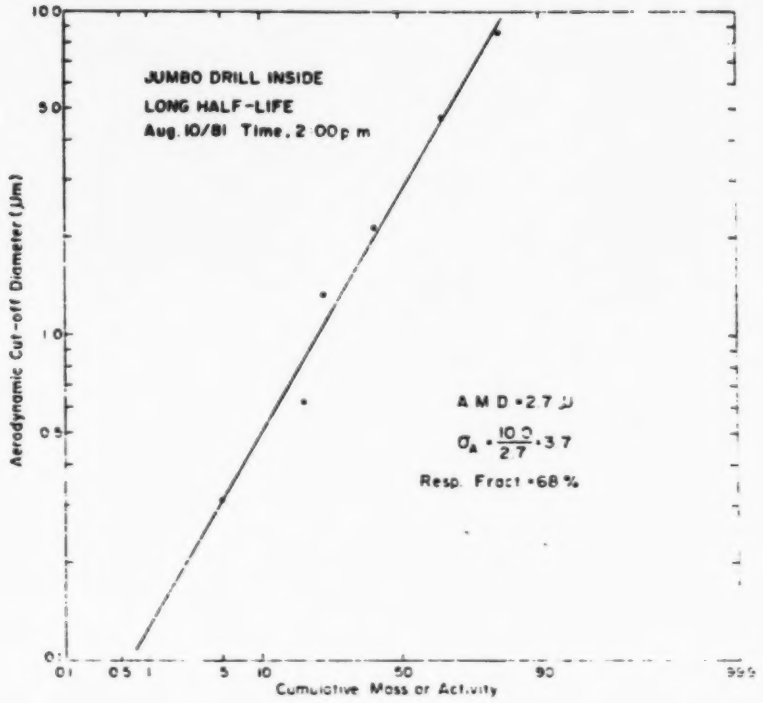


Figure 5 E. Particle Size Distribution of Uranium Ore Dust in Drill Cab

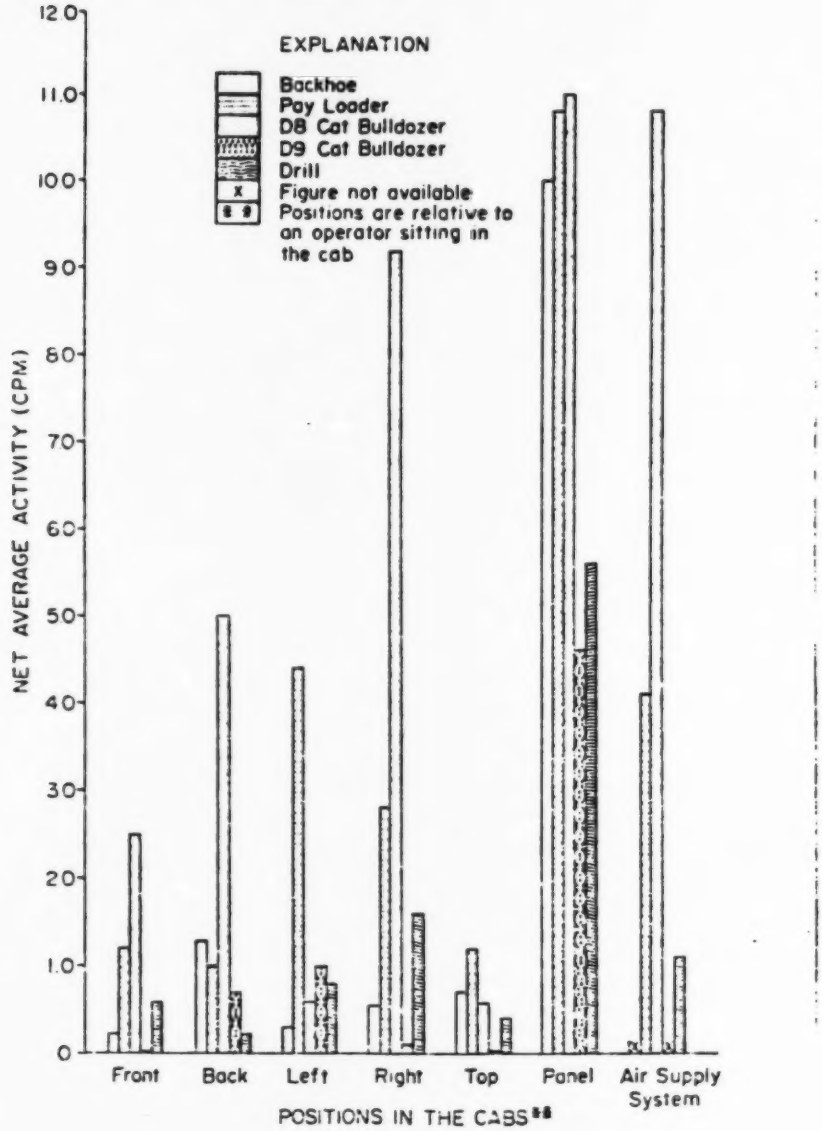


Figure 6 A. Surface Contamination of Equipment Cab (Excavating and loading Equipment)

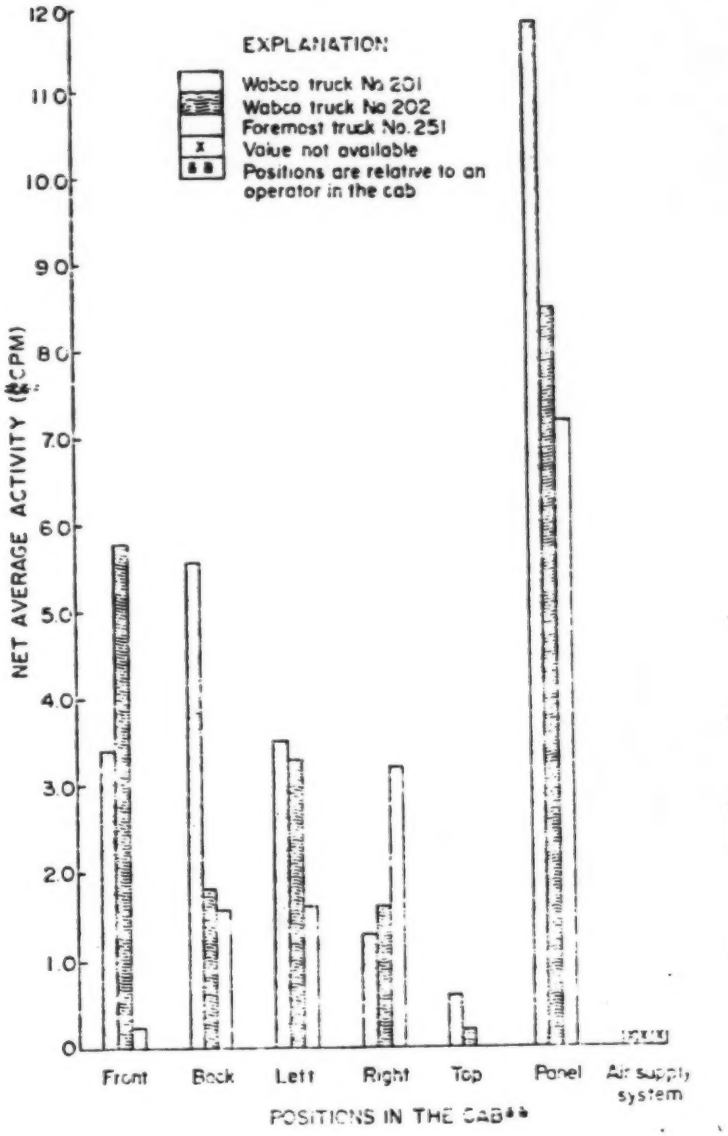


Figure 6 B. Surface Contamination of Equipment Cab (Transport Equipment